AN INVESTIGATION OF COMPACTION VARIABILITY FOR SELECTED HIGHWAY PROJECTS IN INDIANA

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by

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AND

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AN INVESTIGATION OF COMPACTION VARIABILITY

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To: G. A. Leonards, Director
Joint Highway Research Project

March 14, 1967

File: 6-36-67B

From: H. L. Michael, Associate Director
Joint Highway Research Project

Project: 9-11-2

Attached is the final report on the HPR Project entitled "An Investigation of Compaction Variability for Selected Highway Projects in Indiana". This report has been prepared by Mr. T. G. Williamson and Professor E. J. Yoder.

The report presents the results of the Quality Control Investigation pertaining to compaction of subgrades and subbases.

Your attention is directed to the following point. The investigation was started at Purdue University during the summer of 1965. The study is a continuation of the quality control work carried out under HPR on plastic concrete. Professor E. J. Yoder was appointed Acting Director of the Research and Training Center in February, 1966, and Mr. T. G. Williamson joined the Research and Training Staff in June, 1966. Due to the fact that the work was not completed before these gentlemen began work at the Research and Training Center, the project was transferred to the Center and was completed there. However, in accordance with the wishes of the Advisory Board this report should be submitted to them for action.

The report will also be submitted to the Highway Commission and to the Bureau of Public Roads for their review and comments.

Respectfully submitted,

Harold L. Michael

Harold L. Michael
Secretary

EJY/lk

Attachment

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ABSTRACT

Construction of a high quality highway demands that a certain amount of inspection be done to insure that it meets the specifications set forth. The use of a statistical procedure for accomplishing this inspection has been proposed in recent years. However, in order to establish this type of control, a knowledge of present construction practices and the control which is enforced is required.

The area of study chosen for this project was compaction control of subbase and subgrade elements as used in rigid pavements. Six selected projects (three subgrade and three subbase projects) in Indiana were investigated with the study designed to accomplish two basic objectives. The first of these objectives was to gather data to determine what level of compaction was actually being achieved using the present standards of inspection and enforcement. Also involved was an investigation of the variability in compaction and the factors that cause this variation. The second objective was then to determine how a statistical quality control program might be developed from these data.

To insure that a realistic estimate of the true level of compaction and its associated variability was being obtained, approximately one hundred field density tests were performed on each project. A testing program recommended by the Bureau of Public Roads was followed. This program consisted of dividing each project into ten units of equal size and performing five randomly located replicate density tests in each of these.

Necessary to the computation of per cent compaction values was the accurate determination of maximum density values for the corresponding field density tests. For the subgrades, a study of the use of a "one-point" field compaction test in conjunction with a family of typical compaction curves showed this technique to be reliable and very useful in the field. A curve of maximum density versus the percent of material passing the No. 4 sieve was developed for each subbase material. This laboratory developed curve was then used as a control curve for use in the field.

The results obtained indicated that the overall level of compaction was in general lower than what was specified. Also, the overall variability in compaction was relatively large indicating a condition of non-uniform compaction. The data showed that more uniform compaction was obtained on the subbase elements than on the subgrades showing an effect of material type. The factor of operator variance in performing the field tests was also more pronounced for the subgrade elements. The overall variability was attributed to the interaction of several factors including overall material type, operator variance and soil variability within a unit of construction.

The compaction data were used to develop a typical statistical quality control program. It was discovered that more tests for a given construction unit than presently specified would be required to insure uniform compaction. However, if the end result desired is that of a given average compaction level for the entire project, then the number of tests required would be approximately the same as the number presently used. The main problem would then be to insure that the tests are properly performed, that the location chosen is truly representative and that the results obtained are enforced.

AN INVESTIGATION OF COMPACTION VARIABILITY FOR SELECTED HIGHWAY PROJECTS IN INDIANA

INTRODUCTION

The application of statistical quality control to highway construction has become a subject of widespread interest during the past several years. The use of statistical techniques in the control of manufactured products has long been recognized by industry as an effective means of controlling quality.

The Bureau of Public Roads has taken the lead in recommending the use of a statistical approach to highway construction control. There are several reasons why statistical quality control is needed in highway construction. First, in many instances it is difficult and often impossible to say whether present sampling and testing procedures (i.e. arbitrary spacing of samples etc.) are adequate to control a construction project. Second, in many cases the engineer must use a judgement factor that affects both the contractor and the highway departments: this judgement may involve a large sum of money. Statistics can be the tool which provides an aid to the engineer and assists him in making better decisions as to the overall quality of a given section of highway construction.

One specific area of highway construction which has received little attention in the past in connection with this type of control has been the construction of subgrade and subbase elements. The construction of these elements of a highway may be likened to an industrial manufacturing process. The finished highway itself is a

manufactured product and some method of quality control must be specified in order to insure a final product that will be acceptable to all concerned. In connection with highways, possibly the control methods should be termed acceptance control as the end result is the acceptance of a finished highway built to certain specifications.

During the past, the specifications and the techniques for insuring that these specifications are complied with have developed through a trial and error process. In many cases, these specifications have evolved with little regard to the actual construction process itself and the inherent variability that exists in the finished product. One reason for this is that little data have been collected to define what this variability is and how it affects performance of the highway.

Specification requirements are of little use unless some means of testing and control are exerted. With estimates of variability at hand, it is possible to develop a statistical quality control testing program based on a better understanding of the capabilities of the process.

It should be noted that the word "statistical" has been applied to the above discussion. It is necessary to recognize that present specifications imply a form of quality control. In most specifications, some form of sampling and testing is performed on the finished product and a judgement as to the overall quality is then made based on these test results. The number of tests involved may be one or several but in general these values are interpreted as being representative of a large quantity of material.

Inherent in the statistical analysis is the ability to make estimates of population parameters from sample statistics and to associate these with estimates of the probability of being wrong. That is, by using statistics, a better judgement of overall quality may be made by accounting for the variability that exists in the construction process. Also, an estimate of the error involved in making this judgement is obtained. In this manner, a more realistic approach to product control may be applied.

PURPOSE OF STUDY

The primary purpose of this investigation was to collect construction data from selected subgrades and subbases by a systematic procedure which would permit an evaluation of variability that exists in present-day construction of these elements of rigid highway pavements. These data were also to become part of the Bureau of Public Roads bank of data relative to the variability of highway construction practices.

The analysis of these field data included an investigation of the factors causing variability and the determination of the relative importance of these factors on the final product. The factors investigated in this analysis included 1) is the variation observed of a random nature? 2) is there a correlation between soil type and variability? 3) did field testing personnel have an effect on the variability?, and 4) is the contractor a contributor to this variability? It was desired to study the magnitude of variance components so that these data could be used to establish a quality control program applicable to construction of subgrades and subbase courses in Indiana.

To accomplish the above, it was necessary to investigate the size of construction unit to be tested as well as techniques that can be used to establish the size of unit. Two approaches were studied, 1) soil type, as determined by standard laboratory classification and density tests was used as a control unit, and 2) an arbitrary length of section independent of material type was considered to be the control unit.

The ideal method of insuring a quality product is to perform a large number of tests on a lot (or unit) of the product and to analyze these data on a statistical basis. The poorest control, on the other hand, would be to perform just one test for a given construction unit and to infer overall quality from the results of this single test. Obviously, neither of these methods is practical from the standpoint of obtaining reliable results at a reasonable cost of time and money. Thus, some compromise method must be attained. A prime objective of this study was, therefore, the determination of what this compromise should be.

Most specifications for subgrades and subbases are based on a per cent compaction value which involves the determination of two values, 1) the actual in-place field density and 2) an arbitrary "maximum" density for the material being tested. During this study, both of these tests were investigated to determine their effect on apparent construction variability and to evaluate different methods of obtaining these values. Major consideration was given to the precision of measuring in-place density and the reproducibility that may be expected. Factors studied included the effect of personnel performing the same test, the effect of material type and inherent errors in the field test itself.

Several techniques for selecting a maximum laboratory density value were investigated. If compaction control is to be based on a laboratory value, the most reliable technique would be to run a standard laboratory compaction test for each and every field density determination but this is obviously not practical. The techniques of 1) using an average control

value applicable to the entire project, 2) breaking the project into soil groups and using an average value for each group, 3) use of a family of typical compaction curves and 4) correlation of maximum density with grain size distribution of the material were studied with the endpoint of determining the most suitable method for establishing a control value. The validity of these different approaches and the reliability of the results obtained were thus evaluated.

Another phase of this study involved the investigation of the validity of various field testing techniques and the correlation of these data with laboratory results. Primary among these were the correlation between: 1) field determined and oven dried laboratory moisture content values, 2) field determined dry sieve analyses and laboratory washed sieve analyses, 3) sand calibration by two methods and 4) one-point field compaction tests and standard laboratory compaction tests.

SITE SELECTION

The sites investigated in this research project were selected using guidelines set forth by the Bureau of Public Roads (5)* modified to fit the conditions in Indiana. In the guidelines established by the Bureau of Public Roads, two primary requirements were recommended. These requirements were 1) three subgrades and three subbases should be tested and 2) each study element was to be built by different contractors.

In addition, to the above, it was considered advisable to select the sites to include as many soil types and geographic locations as possible. A further restriction was placed on the selection by the construction program of the State Highway Commission, since these sites were to be normal projects during the summer construction season.

In some cases both the subgrade and subbase at a given site were tested. However, in these situations, the two pavement elements were built by different contractors.

For the remainder of this report the projects will not be designated by name but rather by arbitrarily assigned numbers: B-1, B-2, and B-3 for the subbases and S-1, S-2, and S-3 for the subgrades. The subgrade projects were on Interstate Construction as were two of the subbase projects. The remaining subbase project was an Indiana State Highway consisting of dual-lane-divided highway construction.

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* Numbers in parenthesis refer to bibliography at the end of this report.

FIELD SAMPLING AND TESTING PROCEDURES

Sampling Plans

The sampling plan used in this study was based on a table of random numbers. In addition, the requirement set forth by the Bureau of Public Roads that all projects or portions thereof tested should contain a minumum of 10,000 cubic yards of material was followed. Also, according to this plan each project was divided into ten sections of equal size; these then constituted the basic control sections for testing purposes.

With these criteria in mind, the first project and element tested was Project S-1 which was divided into ten sections, each 3000 feet in length by 24 feet wide. According to the Indiana State Highway Commission, (12), subgrade material is defined as "that part of the road intended to receive base or surfacing material". The subgrade is normally assumed to be the top 6 inches of material immediately below the subbase for rigid pavements. Using these values, a total of 13,333 cubic yards of material was involved in Project S-1. This value exceeded the required volume.

As the field testing progressed, it became evident that it would be necessary to reduce the size of testing area in order that the field testing schedule would be compatible with the pace of construction. This was especially critical for the subbase element. Therefore, the size of the test section in most cases was reduced to 2000 feet by 24 feet, resulting in slightly less than 10,000 cubic yards of material being tested.

For the subgrade material on Project S-1, it was possible to use the recommended 3000 foot control sections as it was not difficult to correlate the testing schedule with the pace of construction. This was due in part to the fact that on this particular project, the subbase material was placed prior to the testing program and there was little interference by construction equipment. On the other hand, the field crews were required to dig through this material in order to test the subgrade. For the other five projects, with two exceptions, control sections were 2000 feet in length. On Project B-2, three of the control sections were adjusted to a size of 1000 feet by 48 feet in order to obtain the required number of tests. This adjustment did not change the overall volume of material tested and, therefore, it is believed it did not affect the results. One section on this project was 2000 feet by 48 feet resulting in a larger overall volume than the other sections. Here again, it is felt that this anomaly did not seriously affect the overall results.

After the control sections were selected, individual test locations were randomly selected within these areas. Test location selection was done in the office. Location of tests was such that any set of test locations could be applied to any field control section, increasing the flexibility of the sampling program to allow for variations in construction schedules.

Five test locations were used in each of the ten control sections resulting in fifty test sites per project. Duplicate tests were performed at each location providing a total of 100 individual field tests for each of the six elements studied. The distance between duplicate test holes was set at six inches. Duplicate tests were made to provide an

indicative of the variance that exists between tests performed at essentially the same location.

The basic sampling plan for both the subgrades and subbases consisted of performing five random duplicate tests in each of ten control sections for each project.

Field And Laboratory Testing

The standard sand cone density test was performed on the subgrade and subbase materials following the procedures set forth in the Indiana State Highway Commission Field Manual (13). It should be noted that in many cases, the subgrade was not tested immediately after final compaction. Dry density was used as the basis for computing all per cent compaction values.

Maximum dry density of each subgrade sample was determined by means of a field one-point compaction test. A field sieve analysis (dry basis) using a nest of three sieves was run for each subbase density test. This was done in order to define material variability, and also to allow for the determination of a maximum dry density value for each field test.

Before starting a day's testing, a sand calibration was performed by each crew. In performing this sand calibration, two replicate sand density measurements were made and if these were in agreement, the average of the two values was used. If a wide variation occurred in these results, a third value was determined and a final sand density was then interpreted from these data.

Two methods of calibrating the density sand were investigated. The first of these consisted of placing the sand in a metal cylinder having an approximate volume of 0.068 cubic feet, and the second method consisted

of determining the volume of the sand cone jug and determining the weight of sand required to fill the jug. The latter technique is the method used by Indiana State Highway Commission personnel.

A typical density and "one-point" compaction test routine consisted of the following series of steps. The test area was first leveled using the field density plate and a sand cone test was performed by the field crew which consisted of two men. The density thus obtained was corrected for the material retained on the No. 4 sieve as described in the Indiana State Highway Commission Field Manual (13). A representative moisture sample was removed and dried on a field stove. The fraction of the sample from the test hole that passed through the No. 4 sieve was next compacted into a cylinder in accordance with ASTM D 698-64T, Method A. The compaction mold was placed on a small concrete block during the compaction process. In many instances, it was necessary for field personnel to adjust the field moisture content of the test sample to what they considered to be optimum moisture content before performing the compaction test. This allowed a more accurate determination of maximum density to be made.

Appropriate laboratory samples were collected from each subgrade project. Individual samples were taken from each test hole for laboratory classification purposes. A 30-pound sample was collected for each "typical" soil encountered along the road with a minimum of ten 30-pound samples being obtained for each project. Standard laboratory classification and compaction tests were performed on these large samples. A moisture sample was sent into the laboratory to provide a comparison between results of field and laboratory determined moisture contents.

All subbase testing was performed on the material between the planer and the paving train, thus insuring that the material was at its final compacted state. As with the subgrades, the first step was to perform the sand cone test. The moisture content of the material was determined by drying the entire sample and then the dry material was passed through the 3/4-inch, No. 4 and No. 10 sieves. A correction for the material retained on the 3/4-inch sieve was determined and applied to the field density value.

To ascertain the validity of the field sieve analysis, the material from each test hole was sent into the laboratory where a washed sieve analysis was performed. A 50 pound representative sample was collected from each test location. A standard washed sieve analysis and a laboratory compaction test were performed on these samples in the laboratory. The laboratory compaction tests were performed according to ASTM D 698-64T, Method C.

It is important to mention that a one week training session was held before sending the personnel into the field. This was done to insure that all personnel were well acquainted with the tests and that each man would follow the same field procedure, providing uniformity from crew to crew.

GENERAL STATISTICS INVOLVED

The collection of data for this study was accomplished during the period June through September, 1965. At the completion of the field testing, the data were checked in the office since most of the computations had been made in the field. The data were then placed on computer punch cards. Typical data included on these cards were in-place density and moisture, laboratory maximum density and optimum moisture content, per cent compaction, project, test number, location and operator.

The statistical analysis of the data was accomplished using standard computer programs for 1) analysis of variance (hereafter called ANOV) tests, 2) homogenity of variance, 3) test for normality of data and 4) multiple regression analyses.

To apply the ANOV technique, the data must satisfy two criteria. First, the data must be normally distributed and second, the variances must be homogeneous. Since the main variable of interest was per cent compaction, tests were performed on this variable to determine if it satisfied the ANOV criteria.

To test for normality, the Kolmogorov-Smirnov test for goodness of fit was used. A description of this test may be found in most statistics books. Results of this analysis showed that per cent compaction was normally distributed for all six projects investigated at the 0.05 level. The Foster-Burr test (8) for homogenity of variance was performed on the ten control sections within each project. Results of this analysis indicated that these variations were homogeneous at the 0.05 level for each project. Having met the two stated requirements, the actual ANOV technique to be used was determined.

The basic analysis of variance employed was a Model II, equal number of observations per treatment design. A one-way ANOV was used with the generalized format as indicated by Table 1.

The analysis shown in Table 1 was performed on two different lengths of control units. The entire projects were first analyzed as individual units with approximately fifty treatments per project (a treatment represents two replicate measurements). Next, each of the six projects was broken into the basic control sections and the ANOV was performed on each of these units. These control sections consisted, in general, of approximately five treatments per section although this number varied from three to seven.

By performing these two different analyses a comparison of variance terms was made between projects as well as between sections with a given project. Results of this comparison were then used in establishing guidelines for a statistical quality control program.

In addition to the one-way ANOV, a nested ANOV was performed to determine project to project variation for a given pavement element. To accomplish this, a factorial ANOV computer program was employed with the generalized results as indicated in Table 2.

This approach shown in Table 2 made it possible to determine if the effect of different projects was a significant factor. An F test was used to determine this significance; these data are presented in the discussion of results.

In determining the number of tests required to use a statistical decision theory for a given construction unit, use was made of the statistical "t" test. Estimates of limits of accuracy were also introduced, based on the "t" distribution. In both cases, use was made of the ANOV data to obtain an estimate of variance.

Table 1

Generalized ANOV (Equal number of tests per treatment) Model II

Source of Variation	Degrees of Freedom	EMS
Means	T-1	$\sigma_{\varepsilon}^{2} + r\sigma_{\tau}^{2}$
Error	T (R-1)	σ_{ε}^{2}

T = number of treatments

R = number of replicate tests per treatment

σ_{ε}^{2} = within treatment variance

σ_{τ}^{2} = between treatment variance

Table 2
Generalized Factorial ANOV

Source of Variation	Degrees of Freedom	EMS
Between Projects	P-1	$\sigma_{\epsilon}^2 + r\sigma_t^2 + tr\sigma_p^2$
Between Treatments	T-1	$\sigma_{\epsilon}^2 + r\sigma_t^2$
Error	PT(R-1)+(P-1)(T-1)	σ_{ϵ}^2

P = number of projects

T = number of treatments per project

R = number of replicate tests per treatment

σ_{ϵ}^2 = error term*

$\sigma_{\epsilon}^2 + r\sigma_t^2$ = treatment within project component

$\sigma_{\epsilon}^2 + r\sigma_t^2 + tr\sigma_p^2$ = project to project component

* It is noted that the error term includes the within replicates component and the interaction effect. This is due to the fact that the interaction effect is actually non-existent since there is no relationship between treatment t_1 of project P_1 and treatment t_1 of projects P_2 or P_3. The computer program is such that this term is added into the within replicates component thus giving the error term.

The relationship between laboratory and field determined moisture contents as well as between laboratory and field sieve analyses were analyzed using a standard weighted regression analysis computer program. It was thus possible to determine operator effect and project or soil type effect on each of these test comparisons by comparing appropriate correlation coefficients and regression line equations.

The brief discussion of the statistical analyses used in the study is introduced to acquaint the reader with the techniques which are employed in the analysis of the results. Further discussion and clarification of these methods will be presented as required.

RESULTS AND DISCUSSION OF RESULTS

Comparison of Testing Procedures

Field One-Point Versus Laboratory Compaction Tests

The field "one-point" compaction test was chosen as the means to determine the maximum laboratory density for each subgrade test. The one-point technique has been investigated by several different agencies and the results obtained from these studies have been favorable. In particular, reference is made to work done in 1938 by K. B. Woods and R. R. Litehiser in Ohio (20). From this original work typical curves of moisture-density were developed for soils found in Ohio (15).

For this study, a set of typical compaction curves for Indiana soils was used (Figure 1). These curves were developed from laboratory data by W. T. Spencer of the Indiana Highway Commission. The curves are plotted on a wet density basis with corresponding optimum dry densities and moisture contents also indicated in tabular form.

A compaction test was performed in the field following ASTM D698-64 T, Method A. The data from this test were plotted on the family of curves and the appropriate compaction curve for the soil determined by interpolation. Standard compaction tests were also performed in the laboratory on some of the soils. A comparison was then made between the maximum dry density values obtained by these two methods (i.e. one-point and laboratory). A total of eighty comparisons were made for the three subgrade projects. Results of this comparison showed the maximum dry densities from the field

tests averaged 3.11 pcf lower than the corresponding laboratory values (see Figure 2). Treating each project individually, the average differences between laboratory and field maximum dry densities were Project S-1, $\bar{x}$ = 2.5 pcf; Project S-2, $\bar{x}$ = 4.3 pcf and Project S-3, $\bar{x}$ = 1.8 pcf.

An insight into the reason for this deviation between field and laboratory values existing may be gained by examining the difference between the tests themselves. In the standard laboratory compaction test, the sample is reused for each point on the compaction curve whereas the field test used in this study did not involve reusing the soil. Studies have shown that reusing the soil will, in most cases, result in higher maximum densities than would be obtained by using a new sample for each compaction point. Also, the laboratory tests were performed on a concrete floor whereas the field test was conducted on a small concrete block on the grade. Because of this difference in test methods, it is possible that more compactive effort was abosrbed by the soil in the laboratory test than in the field test with resulting higher values of maximum density in the former case.

It is noted in Figure 2 that in some cases, extremely large deviations (as much as up to 12 pcf) existed between results of the one-point and laboratory compaction test. These large deviations are attributed to operator error and are not felt to be truly indicative of the relationship between these tests. A study of the occurrence of large deviations (values greater than 4.0 pcf) indicated that neither an individual project nor an individual operator had a direct effect on the wide variations between laboratory and field test results.

Figure 2 also shows a comparison between the results of this study and those obtained in a comprehensive investigation at Purdue University by L. G. Wermers (19). Results of Wermers' study, based on 861 observations, of maximum density as determined from a standard laboratory compaction test compared to the value from the one-point compaction test showed that 92 per cent of the one-point values were within 4.0 pcf of the laboratory curve value. Results of this study, based on 80 comparisons showed 70 per cent of the one-point data to be within 4.0 pcf of the laboratory value. If it had been possible to make more comparisons in this study, it is felt that the results of these two studies would more closely approximate each other.

The Indiana typical compaction curves do not apply to materials having wet densities exceeding 142 pcf. Whenever this value was exceeded in this study use was made of the Ohio typical compaction curves. Incidental to this study, a comparison was made between per cent compaction as determined by the Indiana and Ohio curves. An average difference of 0.65 percentage points was observed, indicating no appreciable difference between results.

The results of this study suggest that the use of the field one-point compaction test is justified and that the results are comparable to those obtained in the laboratory. It should be noted that, for future field work, the Indiana curves should be extended for both higher and lower density materials to make them self-sufficient. An alternative to this would be to adapt the Ohio curves per sé.

The one-point test has an added advantage over the laboratory test, in so far as compaction control is concerned, in that it permits selection of the correct control curve based on data obtained at a specific test location. Further comparisons of this technique with other techniques will be made in subsequent paragraphs of this report.

Field and Laboratory Measurement of Moisture Content

The ability of the operator to accurately measure soil moisture content in the field is a prerequisite to the use of the typical compaction control curves and the determination of in-place dry density. Moisture content was determined in this field study by drying a sample of the material on a portable field stove. To check the accuracy of this drying method, selected samples were sent into the laboratory and oven dried at 105°C.

A total of 325 of these check tests were made. The results of this comparison showed 91.7 per cent of the field and laboratory moisture contents to be within $\pm$ 2 per cent of each other with an overall average deviation of $\pm$ 0.8 per cent. Figure 3 shows a plot of these data with the dashed lines indicating a range of $\pm$ 2 per cent deviation from the mean. The correlation coefficient for this plot is 0.843. These results indicate an excellent agreement between laboratory and field moisture determinations.

The moisture content data were also categorized into individual projects and by operator. A regression analysis was performed on each of these groups. It was assumed that any result having a difference of greater than 4.0 per cent moisture indicated an operator error and these

data were not included when comparing different projects. Results of these analyses are presented in Table 3.

The data in Table 3 indicates that one project (S-2) and one team of operators (1 and 2) had correlation coefficients that were very low in comparison to the others suggesting that both project and operator effected the accuracy of field moisture content determination. The soil on Project S-2 was granular accounting in part for the relatively poor correlation. However, operators 1 and 2 performed all of their tests on this particular project and may have been careless in their work. It is not possible to say which of the factors (operator or project) had the greatest effect on the accuracy of the results.

Field Dry, and Laboratory Wet, Sieve Analysis

The field control curves adopted for the subbases related amount of material passing the No. 4 mesh sieve (laboratory washed values) to maximum ASTM Density D698-64T, Method C. Since use of these curves in the field is of necessity based upon a dry sieve analysis, it became necessary to establish a correlation between laboratory washed values and field dry values. This correlation was established by performing a regression analysis on test results from Project B-1 (see Figure 4).

Data in Figure 4 indicate excellent correlation between field and laboratory values with a correlation coefficient for the No. 4 mesh sieve of 0.974 and a standard deviation of 0.85.

Table 4 shows a summary of correlation coefficients and standard deviations for data obtained from three projects and from three different

Table 3 Summary of Regression Analysis of Moisture Content Comparisons

(a) Data Grouped by Operator

Operator	Number of Observations (n)	Correlation Coefficient (R)	Standard Deviation (σ)
All Data	325	.8[illegible]3	2.67
[illegible]	149	.925	1.77
[illegible] & 2	99	.741	3.77
[illegible]	31	.952	0.67
[illegible]	26	.940	1.30

(b) Data Grouped by Project
(all data with deviations exceeding ± [illegible].0 per cent excluded from analysis)

Operator	Number of Observations (n)	Correlation Coefficient (R)	Standard Deviation (σ)
All Data	[illegible]13	.867	2.46
[illegible]	59	.[illegible]61	[illegible].[illegible]2
[illegible]	13[illegible]	.[illegible]44	3.02
[illegible]	79	.942	[illegible].98

Table 4

Summary of Regression Analyses for Sieve Analyses Comparisons

Project	Number of Observations	3/4" Sieve	No. 4 Sieve	No. 10 Sieve
B-1	101	R=.968	R=.974	R=.9[illegible]
		σ=0.86	σ=0.85	σ=1.3[illegible]
B-2	10	R=.997	R=.986	R=.9[illegible]0
		σ=0.50	σ=1.35	σ=1.84
		R=.977	R=.955	R=.961
[illegible]	10	σ=1.04	σ=1.08	σ=1.17

sieves. It is apparent that precision of field testing is a function of sieve size with the larger sizes giving more accurate results than the smaller sizes. It was not possible to compare accuracy of operators as no field record was kept of the individuals performing the sieve analysis.

Comparison of Two Density Sand Calibration Techniques

At the outset of this field study, it was decided that the sand for the in-place density test should be calibrated by making use of a steel mold of known volume. This technique varied from the procedure used by the Indiana State Highway personnel which consists of calibrating the sand in the sand cone jug itself. To compare these two techniques, the density sand was calibrated by both methods during part of the field study.

Based on a total of thirty comparisons an average difference in sand density by the two methods of 0.6 pcf was obtained. A tabulation of these data is given in Table 5. In all cases, the calibration in the jug resulted in densities equal to, or higher than, those obtained in the mold. The maximum difference was 1.2 pcf. These differences were of such a magnitude that they had negligible effect on the in-place density test calculations suggesting that either method may be used with equal confidence. Calibration in the mold is recommended due to the possibility of breaking a glass sand cone jug and thus delaying work while a new one is being obtained and calibrated.

It is noted from the data that several projects and teams of operators were involved in these tests. However, no operator or project effect is apparent and the deviations discussed are representative of all projects and operators.

Table 5
Comparison of Sand Density as Obtained by
Jug Calibration and Mold Calibration Techniques

Project No.	Operator No.	Sand Density by Jug Calibration (lbs./ft.^{3})	Sand Density by Mold Calibration (lbs./ft.^{3})	Deviation Jug-Mold
B-2	1,4	96.4	95.4	1.0
B-2	1,4	96.7	95.7	1.0
B-2	1,4	96.4	95.9	0.5
B-2	1,4	96.6	95.8	0.8
B-2	3,5	95.9	95.1	0.8
B-3	6	96.3	96.3	0.0
B-3	2	96.4	96.0	0.4
B-3	2	96.3	95.8	0.5
S-1	3,5	95.6	95.1	0.5
S-1	3,5	95.6	95.1	0.5
S-1	3,5	95.9	95.2	0.7
S-1	3,5	95.9	95.6	0.3
B-2	3,5	95.4	95.4	0.0
B-2	3,4,5	95.7	94.5	1.2
B-2	3,4,5	95.6	94.7	0.9
B-2	3,4,5	95.7	94.7	1.0
B-2	3,4,5	95.7	95.5	0.2
B-2	3,4	96.1	95.2	0.9
B-3	3,4	96.0	95.0	1.0
B-3	3,4	95.8	95.0	0.8
B-3	3,4	96.2	95.7	0.5
B-3	3,4	96.2	95.4	0.8
B-3	3,4	96.2	95.5	0.7
B-3	1,2,3	96.0	95.6	0.4
B-3	1,2	96.2	95.8	0.4
S-3	2,3	96.1	95.8	0.3
S-3	2,3	96.0	95.8	0.2
S-3	2,3	96.2	95.8	0.4
S-3	2,3	96.0	95.8	0.2
S-3	2,3	96.1	95.6	0.5
S-3	2,3	96.2	95.4	0.8

Maximum Density and Per Cent Compaction Comparison

Maximum Density of Subbases

The current practice used in controlling subbase compaction in Indiana is to compute per cent compaction based on a laboratory compaction test maximum density. One value of maximum density is generally employed over an entire project. Use of this procedure may be suspect since material is generally non-homogeneous over a construction project.

Having verified that laboratory sieve results for relatively coarse sieves could be reproduced in the field, control curves were developed based on grain size variations. The No. 4 sieve was chosen as the control sieve because of ease in performing field sieve analyses.

Curves relating maximum dry density to percentage of material passing a No. 4 sieve (with plus 3/4" material removed) were developed for each project (Figures 5, 6, and 7). Techniques for accomplishing the above are based on those presented by Yoder and Woods (21). Calculated densities based on the method proposed by Humphres (11), were used as a guide for developing the control curves shown in Figures 5, 6, and 7. Smooth curves having the approximate shape of the calculated control curves were drawn through the data plotted from the laboratory compaction tests and these curves were defined as the subbase field control curves.

Using the above control curves, values of maximum dry density were determined for each individual in-place field density test and these values were used to compute per cent compaction. Three techniques for determining maximum dry density from the control curves were studied: 1) values interpreted from the curves using field sieve data, 2) values obtained from these curves using laboratory sieve data and 3) an average

value corresponding to the range in percent of material passing the No. 4 sieve observed for each project. Per cent compaction values were then calculated using these appropriate maximum dry density values.

A comparison of these techniques indicated that each of the three methods resulted in approximately the same distribution of data. Figure 8 presents a comparison of results using methods 1 and 2 described above while Figure 9 shows a comparison based on methods 1 and 3. These data indicate that use of either a field sieve analysis value, or an average value of material passing the No. 4 sieve yields about the same results.

It must be noted that each of the subbases studied had a relatively low range in values of material passing the No. 4 sieve, and in particular, the data generally fell on the flat portion of the control curve. In contrast to this, if the material being tested had plotted on the steep portion of the control curve, the use of an average value of maximum density would have been questionable.

Maximum Density of Subgrades

Two techniques for determining maximum dry density were investigated. The first of these was the use of a field one-point compaction test which has previously been discussed. The second approach involved the use of an average maximum density value for each soil type encountered. To identify the different soil types present on each subgrade project, laboratory compaction and classification tests were performed on representative samples from the roadway.

Results of the classification tests are shown in Figure 10 which is a plot of liquid limit versus maximum dry density. Indicated on Figure 10 are four soil groups and corresponding average maximum dry density values for each group. A fifth soil group (not indicated on the Figure) having a maximum dry density of 98.8 pcf was also used in the analysis. For this latter group, large samples were not obtained in the field and the average maximum dry density value is based on field one-point compaction data rather than on laboratory data. The five soil groups were used in the analysis of data from each project.

Also indicated on Figure 10 is a line representing similar correlation data from a study made by K. B. Woods and F. R. [illegible] ([illegible]). The close agreement between these data and the data of this study lend validity to the use of this approach to define soil groups. Further discussion concerning the selection of the limits indicated for each soil group is presented in a later section of this report [illegible] material [illegible].

To incorporate these basic soil groups, a classification test was performed on representative samples from the in-place density tests. On this basis, each field test was assigned to one of the five soil groups and per cent compaction was computed using the appropriate maximum densities. Figure 11 shows the frequency distributions of per cent compaction using this technique and the one-point compaction test data for Project S-3.

It is observed in Figure 11 that average percent compaction is higher, and standard deviation is smaller for data based on the one-point compaction tests contrasted to use of average values for the soil group. One half of the values based on the soil group approach showed an average compaction less than 95 percent, whereas the corresponding figure for the one-point compaction approach was only 25 percent of the tests.

The same trend between these two techniques for computing percent compaction was also observed for the other two subgrade projects. It is difficult to determine which of these approaches gives the most correct answer as they are merely a comparison of two results of which neither may be the correct solution. However, it should be recognized that the approach based on soil groups is a laboratory technique and is not conducive to simple field application. On this basis, it would appear that the use of field one-point compaction tests would be the better of the two techniques for field use.

Use of Dry Density vs Wet Density

Throughout this study per cent compaction was determined on the basis of dry density values. This was necessary since, due to construction schedules and the schedule of this project, it was not possible in many instances to test the subgrades immediately after final compaction and, therefore use of wet densities would have been questionable due to possible drying out of the compacted soil.

A comparison of moisture content at time of test and the optimum moisture content is shown by Figure 12 for the three subgrade projects. This plot shows that two of the projects were tested (on the average) at some moisture content less than optimum while the soil on the third project was slightly over optimum.

Since the Indiana State Highway Commission normally computes per cent compaction based on wet density, a comparison was made between results obtained using both wet and dry density. It was found that a higher average value of per cent compaction was obtained using dry density for the two projects tested dry of optimum. However, on Project S-3 which was tested at near optimum moisture content, use of wet density resulted in approximately the same per cent compaction values as obtained using dry density. These data were expected and they underscore the need for testing the subgrade *immediately* after compaction if the control is to be based on wet density values.

Variability Observed

Per Cent Compaction

To determine the distribution of per cent compaction results, tests for normality using the Kolomogorov-Smirnov test were performed for all projects. In all cases the data was found to be normally distributed with the results of this analysis as shown in Table 6.

Also, a test to determine homogenity of variance between control sections within a project was performed. The test chosen to determine homogenity was the Foster-Burr Test, which uses a Q-test for equality

Table 6

Summary of Tests for Normality of Per Cent Compaction Data

$\alpha = 0.5$

Project	Maximum Difference From Data	Tabular Critical Value *	Accept Hypothesis of Normality **
(1)	(2)	(3)	(4)
[illegible]-1	.0339	.133	Yes
[illegible]-2	.0503	.136	Yes
[illegible]-3	.0266	.137	Yes
[illegible]-1	.0437	.136	Yes
[illegible]-2	.0494	.128	Yes
[illegible]-3	.0101	.122	Yes

* Computed from $\frac{1.36}{\sqrt{n}}$ where n = number of observation

** Normality exists if value from column (3) exceeds value of column (2)

of variances and was chosen due to its applicability to small sample sizes with unequal degrees of freedom. A detailed description of this test may be found in reference (8). For this study the sample size is taken as the number of control sections per project. The results of this analysis are shown in Table 7 and indicate that homogenity of variance did exist between control sections for each project. The distribution of per cent compaction for the three subgrades studied is shown in Figure 13. The average per cent compaction values based on one-point compaction test maximum dry densities were: S-1, $\bar{x}$ = 100.6: S-2, $\bar{x}$ = 96.8: and S-3, $\bar{x}$ = 98.2. Also indicated are the standard deviations for these distributions. It is noted that the range in per cent compaction observed ranged from approximately 85 per cent to 110 per cent for all three projects indicating a relatively wide spread in compaction results. Reference to Figure 13 shows that Project S-1 had the highest average per cent compaction and that Project S-3 had the lowest standard deviation (narrowest range in per cent compaction) indicating more uniform compaction for this latter project. Project S-2 had the poorest control as evidenced by its lowest average per cent compaction and largest standard deviation.

Figure 14 shows cumlative polygons for the three subgrade projects. Based on a specified value of 100 per cent compaction, reference to this figure indicates that approximately fifty per cent or more of the tests performed for each project failed to meet this specification. Project S-2 indicated the poorest control with 75 per cent of the tests on this project falling below the specified value.

Table 7

Summary of Foster-Burr Homogeneity of Variance Tests

$\alpha = .05$

Project	No. of Samples	Q Statistic From Data	Tabular Q Statistic	Accept Homogeneity Hypothesis *
(1)	(2)	(3)	(4)	(5)
S-1	11	.1225	.126	Yes
S-2	10	.1205	.138	Yes
S-3	10	.1379	.138	Yes
B-1	11	.1228	.130	Yes
B-2	11	.1125	.126	Yes
B-3	10	.1198	.138	Yes

* Accept hypothesis of homogeneous variances if values in column (4) exceed values in column (3)

The distribution of per cent compaction for the subbase projects, based on maximum densities from the control curves, are presented on Figure 15. Also indicated on Figure 15 are average per cent compaction values and corresponding standard deviations. The average per cent compaction values are observed to be well below 100 per cent. However, the standard deviations are noticed to be lower than were obtained from the subgrades indicating more uniform control of density was obtained for the subbase. The reason for this uniformity of compaction is probably due to the relative homogenity of the subbase material in comparison to that of the subgrade soils. Figure 16 shows cumulative polygons for the subbase data. It is to be noted again that all of the subbase tests showed degree of compaction less than 100 per cent.

Material Variability

An indication of subgrade soil variability was obtained by examining the results of two types of laboratory tests performed on samples obtained during construction. These tests were 1) laboratory compaction tests following procedures specified in ASTM D698-64T, Method A, and 2) laboratory plasticity tests following either the ASTM standard specifications or the one-point liquid limit technique described by H. Y. Fang (7). Periodic liquid limit and plastic limit check tests inserted into the laboratory testing schedule indicated that the laboratory technician was achieving a high degree of reproducibility in his testing.

Compaction curves developed for each project are plotted on Figure 17, 18, and 19, indicating a wide range in maximum dry densities for the soils sampled. It is suggested here that an alternative to the use of the typical Indiana curves as shown by Figure 1 would be to develop a set of typical

curves for each project and to use these for compaction control. This could be accomplished in a field laboratory and eliminate the need for sending samples to a central laboratory.

A basic aspect of subgrade soil variability was involved in the sampling procedure for these laboratory compaction tests. It was felt that by sampling the material from the general area in which the replicate sand cone tests were performed a true estimate of the compaction curve for this material could be obtained. The assumption involved with this sampling was that material variability in a relatively small area would be minor. Six duplicate samples (i.e. an individual 30 pound sample taken from the area surrounding each of the replicate sand cone test holes) were obtained for subgrade Project S-1.

Standard laboratory compaction tests were then performed on each of these samples (labeled A and B) and the results are shown by Table 8. These data suggest that soil variability can exist in relatively small areas as shown by the range in maximum density values for tests 34 A and B and tests 36 A and B. At the same time the rest of the duplicate tests indicate that there is only a minor difference in maximum density values for the samples selected.

Data from classification tests performed on the samples are also indicated on Table 8 along with their corresponding AASHO classification. On this basis, only tests 38 A and B would indicate a different soil type as defined by this type of classification system. It is concluded that in general some soil variability is possible in relatively small areas, but that this probably would only be detected by performing laboratory tests.

Table 8

A Comparison of Maximum Dry Density and Optimum Moisture Content Values for Duplicate Field Samples for Project S-1

Test Number	Maximum Dry Density (pcf)	Optimum Moisture Content (%)	Liquid Limit (%)	Plasticity Index	Classification AASHO
27 A	118.7	13.7	32.5	13.5	A-6 (8)
27 B	119.3	13.5	36.0	15.2	A-6 (9)
32 A	117.4	14.4	33.9	14.3	A-6 (6)
32 B	115.8	15.4	34.6	13.9	A-6 (8)
34 A	113.5	15.4	41.5	18.4	A-7-6 (11.5)
34 B	110.6	14.3	41.6	16.9	A-7-6 (9)
36 A	123.0	13.4	30.2	12.3	A-6 (7)
36 B	119.7	13.3	31.0	11.9	A-6 (8)
37 A	121.2	12.6	28.1	8.6	A-4
37 B	122.6	11.0	----	----	----
38 A	112.6	17.3	41.3	17.6	A-7-6 (11)
38 B	113.5	15.9	37.6	14.6	A-6 (9)

Figure 10 shows the laboratory maximum density as a function of liquid limit. Data on Figure 10 suggested a possible technique for establishing soil groupings and a further study was undertaken. Results of this analysis are indicated by Figures 20, 21, and 22. These figures show the relationship between plasticity index and liquid limit for each project. Soil groups were established for each project. Appropriate average maximum dry density values were determined for each group by averaging the compaction test results falling into a given soil group.

The soil groups mentioned above were arbitrarily indentified as Soils A, B, C, D, and E. Table 9 presents actual liquid limit and plastic limit ranges for each of these groups.

It was observed that the soil groups (allowing for the slight differences in liquid limit and plasticity index values) were repeated from project to project with soil groups B and C existing on every project. A comparison of average maximum dry density values for the soil groups indicated that these values are approximately constant for a given soil group regardless of project. Based on these results, a classification test performed on the material from the in-place density tests permitted placing the soil into one of these groups with an appropriate maximum density value being used to determine per cent compaction.

Figure 23 is introduced at this time to show the distribution of the soil groups for Project [illegible]-3. It is noticed that the occurrence of the soil types is random and that they are of a reoccurring nature from one end to the other end of the project. This same trend was also

Table [illegible]

[illegible]

[illegible]	[illegible]	[illegible]		
		[illegible]	[illegible]	[illegible]
	[illegible] Range		[illegible]	
A	[illegible] Range		[illegible]	
	[illegible] Range	[illegible]	[illegible]	[illegible]
[illegible]	[illegible] Range	[illegible]	[illegible]	[illegible]
	[illegible] Range	[illegible]	[illegible]	[illegible]
	[illegible] Range	[illegible]	[illegible]	[illegible]
	[illegible] Range	[illegible]		[illegible]
[illegible]	[illegible] Range	[illegible]		[illegible]
	[illegible] Range	[illegible]		
[illegible]	[illegible] Range	[illegible]		

observed for the other subgrade projects. This variability necessitates the accurate identification of the soil groups as they occur along the project if the proper maximum density, based on classification, is to be applied for routine control. This latter point would generally preclude the adoption of this technique for field use.

The grain size analyses were used to define subbase material variability. An extensive study was made of data from Project S-1 as an example since previous data indicated that subbase variability was similar from project to project. Over 100 samples from Project S-1 were wash sieved through a nest of sieves including the No. 4, No. 40 and No. 200 sieves. The results are shown on Figure 24. This figure indicates that a relatively wide range in grain size characteristics was observed for this project. Ranges in per cent passing for the other two projects for these sieves based on ten randomly selected samples are indicated in Table 10 along with the values for Project S-1.

These data indicate that material variability was approximately the same for all projects although Project S-1 contained considerably more material finer than a No. 200 sieve than did Projects S-2 and S-3. It is important that possible effects of grain size variability be recognized by accounting for it in the determination of appropriate maximum density values.

Factors Influencing Observed Variability

Variance Terms

In determining the effect of each of the individual factors involved on the overall variance, results from either a nested analysis or one-way analysis of variance were employed. Models of these are indicated in Table 1 and 2. The one-way analysis of variance, which was the

Table 10

Ranges Observed in Laboratory Sieve Analysis Data for Subbase Materials*

Sieve	Project B-1 (%)	Project B-2 (%)	Project B-3 (%)
No. 4	58-82	53-78	63-79
No. 40	9-23	11-33	14.7-30
No. 200	4-14	2.8-8.5	3.3-7.5

* Note: Data in Table represent per cent of total material passing a given sieve

primary technique used involves two basic variance terms, these being 1) within treatment variance and 2) between treatment variance where a treatment is defined as a pair of duplicate (six inches apart) field tests.

The between treatment variance represents variation in compaction from station to station along the project and is attributed to three main factors: 1) material variability, 2) contractor (or compaction technique) variation and 3) technician variability.

The within treatment variance represents variability due to 1) technician variability 2) inherent inconsistency in the test itself (sand cone or one-point compaction test) 3) soil variability within a small testing area and 4) compaction variability. Soil variability and variation in the compaction process were assumed to be of less importance than the other two factors considering the close proximity of the pairs of tests. However, this should not be interpreted as saying that these factors can be ignored in the analysis. This leads to the suggestion that the major part of the within treatment variance term is attributable to testing or technician variance with soil type and compaction variability also contributing in some part. This term is hereafter designated as "replicate testing variance".

Variation Due to Different Projects

A nested analysis of variance was used to test for equal means of per cent compaction between projects. This was done on the basis that all contractors were working towards the same compaction specification and thus should (under ideal conditions) obtain similar results. An F-ratio was computed for the data and this value used to test the hypothesis of equal means with the requirement that the hypothesis of equal means is rejected.

if the computed F value is greater than the corresponding tabular value. Results of these analyses as shown by Tables A-1 and A-2 of the Appendix, indicated a significant difference between means of per cent compaction existed for each project at the 95% acceptance level.

A one-way ANOV was performed for the data of each individual project (Tables A-3 and A-4 of the Appendix). In all cases, the variance between treatments within a project was found to be significant indicating a further breakdown of data was required. On the basis of these results, it was decided that each project should be divided into the basic control sections for further study of the variance involved.

Within Project Variability

Each project was analyzed using a one-way ANOV for the basic control sections within each and the between treatment variance terms were tabulated. Results as indicated in Table A-5 show that the between treatment variances varied widely from one control section to the next within a given project. Further, the variances were in general, smaller for the subbases in comparison to the subgrades. Those sections having small between treatment variance terms are indicative of uniform compaction. Conversely, non-uniform compaction is indicated when the control sections have large between treatment variances.

Figures 25 and 26 indicate the actual per cent compaction values for each individual test as well as average values for each control section for parts of Projects S-5 and B-1. It is observed that wide variations in per cent compaction occurred over relatively short lengths of roadway, especially for the subgrade soils. Also, the magnitude of this variation is observed to vary from section to section and appears random in nature.

Table A-6 gives the average per cent compaction obtained for each control section of the three subgrade projects and shows the nature of variability from section to section. Both operator effect and material variation are partly responsible for this variation and are discussed in the following sections.

Material Type Effect

A general effect noticed was the large difference in both the between variance terms and the within variance terms when comparing the two pavements components in general. In particular, the within variance terms for the subbase were observed to be much smaller than those recorded for the subgrades. Typically this variance term for the subbases was approximately 4, compared to approximately 14 for the subgrades (Tables A-3; A-4). Overlay sheets for Figures 25 and 26 show these per cent compaction variations between individual test locations for both a subgrade and subbase project indicating a much closer agreement for replicate subbase tests than was observed for subgrades.

Several factors are felt to be the cause of the difference between subbase and subgrade results. First, difficulty is generally encountered when performing the in-place density test itself. In most instances the subgrades in this study were tested after a period of time had elapsed from initial compaction and therefore, some drying out of the subgrade occurred. This drying out resulted in the material becoming very hard which increased the difficulty of performing the sand-cone density test On the other hand, the subbases were generally tested immediately after compaction and were therefore near optimum moisture content which allowed a density hole to be dug relatively easily. The average difference between

replicate in-place density tests for subgrades was 4.1 pcf whereas this value dropped to 3.3 pcf for the subbases. A summary of these values by projects is given in Table 11.

Project S-2 showed a particularly high average difference between replicate tests (4.95 pcf); this is attributed to the large proportion of stones larger than a No. 4 sieve encountered which in turn increased the difficulty of performing the sand cone test.

A second possible factor leading to higher within variances for the subgrades is the fact that this term includes all field testing variances. For the subgrades this included both the sand cone density test and field one-point compaction test whereas the subbase testing involved only the sand cone test. This difference could result in a larger variance term for the subgrades due to larger chance for an operator variance existing.

Also, if it is assumed that variations in soil type can exist over relatively small areas, the non-homogenity of the subgrades in comparison to the subbases would lead to higher within treatment variances. This factor of soil homogenity also has an influence on the between treatment variances. Also, the general nature of the materials involved was no doubt a factor. The subbase materials were much less variable than the subgrade soils and this homogenity of material along the project provided for a more uniform compaction condition.

As previously indicated the subgrade soils were divided into five basic groups and a study of per cent compaction based on the soil groups was made. Table A-[illegible] presents the frequency of occurrence of these five soil groups for Project S-1 and S-2 and the corresponding average per cent compaction for each. Considering these data for all projects

Table 11

Average Differences Between Sand Cone Density Tests for Replicate Tests

Project	Number of Replicates	Average Difference Between Sand Cone Density Values for Replicate Tests (lbs./ cu. ft.)
S-1	48	3.32
S-2	48	4.95
S-3	49	4.18
B-1	51	4.15
B-2	55	3.35
B-3	50	2.24

together, average per cent compaction ranged from 92% for Soil A to 103% for Soil E. Likewise, average dry density values ranged from 122.6 pcf for Soil A to 101.7 pcf for Soil E. These data indicate that little difficulty was encountered in obtaining 100 per cent compaction for the low density soils but that as maximum dry density increased the per cent compaction level achieved decreased. A possible conclusion from this would be that an erroneous value of maximum density (representing a lower density soil) for compaction control may have been applied to some soils encountered on a project which would partially account for the decrease in per cent compaction with an increase in maximum density. This, however, cannot be ascertained with certainty.

In analyzing each project individually, a similar trend of high per cent compaction for soils having a low maximum density value was noted for the soils involved on Projects S-1 and S-2. However, on Project S-3 the compaction obtained was approximately the same for the primary soils groups involved, although they varied in maximum density characteristics.

An analysis of the two soil types (B and C) that were encountered on all three projects showed that approximately the same per cent compaction was achieved for these soils regardless of project or contractor.

A comparison of between treatments and within treatment variance terms for Project S-3 for the original 2000 foot control sections was made with the variance obtained when soil type was used as a basis for comparison. This is shown by Table 12. Results of between tests variance for soil type sections within a project showed the same wide variation existed as were determined using the arbitrary 2000 foot control section, indicating little difference in precision of the two techniques.

Table 12

A Comparison of Variance Terms
Using a Constant Size Control Section Versus Sections
Based on Soil Class Groups

Project S-3

a) Data based on Soil Classification Groups as defined in this report and corresponding Group Maximum Density Values			b) Data based on arbitrary 2000 foot control section and one-point compaction test maximum density values		
Field Tests Involved	Between Treatment Variance	Within Treatment Variance	Field Tests Involved	Between Treatment Variance	Within Treatment Variance
4,5	31.06	3.49	1-5	7.08	1.70
1,3	0	.37	6-10	5.84	4.84
6-10	6.64	3.39	11-15	40.46	1.98
11-15	42.67	7.77	16-20	7.62	3.04
17,19	51.36	4.43	47-50	0	46.50
16,18,20 46-50	2.05	19.94	21-25	13.97	5.90
21,22,24	11.91	7.37	31-35	0	12.96
23,25;31-35 37-39	22.19	6.52	36-40	18.69	18.36
27,28,36,41 43,44	16.01	9.27	41-44	8.95	3.25
26,29,30	23.41	15.21	26-30	9.63	13.43
Entire Project	17.19	8.83	Entire Project	8.03	12.69

Effect of Testing Personnel

A study of within treatment variance, which is primarily an indication of operator variance plus inherent testing variance, provided an insight into the magnitude of operator variance and its relationship to the [illegible] variance observed. An examination of the within variance terms for the subbase projects showed that this value decreased considerably as the testing program progressed. That is, this value was highest for the first project studied and lowest for the last one tested indicating that as the operators gained experience in performing the field test their results became more consistent (See Table A-4). The importance of this observation lies in the fact that as the within variance term decreases the required number of tests to insure a given level of quality also decreases.

The above trend was not as noticeable for the subgrades although the error term for the last project tested was smaller than that for the first one studied (See Table A-[illegible]). It is noted that the first project was tested after some period of time had elapsed from final compaction whereas the last project was tested at the time of final compaction. The highest subgrade error term was on Project S-2 which has been previously indicated as being composed of material in which it was difficult to perform the in-place density test. Thus, differences in soil characteristics and the amount of drying that took place before field testing [illegible] to account for the fact that operator experience had little effect on the results obtained on the subgrades.

Table A-[illegible] presents the within treatment variance terms for [illegible] projects investigated broken down [illegible] appendix [illegible].

variability occurs even when material and operator effects are held more or less constant. For the subgrade it must be realized that the soil itself is highly variable and thus can lead to compaction variations regardless of the operators involved in the testing.

The general conclusion concerning construction variability is that the factors discussed, and possibly others not studied, are interrelated and must be analyzed as an overall variability. The variability was in evidence on all the elements investigated indicating that it is of a universal nature.

Guidelines for a Statistical Quality Control Program

One of the first factors to consider when setting up control procedures is to determine the appropriate size of control section to be used. One technique previously discussed in this paper would be to divide the project into sections on the basis of soil type. However, it was decided that this technique was not conducive to field use due to the difficulty involved in identifying these soils. Another approach would be to establish the control section on the basis of a day's construction of a particular element (subbase or subgrade). However, if a constant number of tests per day is specified the number of tests per unit of length obviously would depend on speed of construction.

It is believed that the most desirable method would be to establish a fixed length (or volume) of material for the control sections. This method allows equal control of the element from section to section thereby insuring more uniformity along the roadway.

Since it is not possible to determine the true mean of percent compaction for a given control section because an infinite number of tests would be required, it therefore becomes necessary to choose a random sample from this population and base the decision of quality on

the mean of the sample. To accomplish this a hypothesis test was used to test for equal means between a given sample size and the total population. Thus, the null hypothesis tested was Ho: $\mu = \mu_0$ versus the alternate hypothesis A: $\mu \neq \mu_0$ where μ = average of n observations and μ_0 = true mean of the population. If the null hypothesis is accepted, then the mean of the sample is said to equal the true mean of the population.

In order to perform this hypothesis test, it is necessary to establish values for several variables. These are the probability errors α and β, an estimate of the true standard deviation or variance and the allowable difference between the sample mean and the true population mean that can be tolerated without detection. This later value is denoted by the symbol [illegible].

Thus, two of the first variables established were acceptance and rejection levels. That is, a permissable probability of rejection of "good" construction (α error) and a permissable probability of acceptance of "bad" construction (β error) must be selected. Due to the nature of these errors, conflicting views concerning the values to be used are bound to occur. The seller, or contractor, in the case of highways would want α to be very small and would allow β to reach a relatively high value. On the other hand, the buyer, in this case the State Highway Commission, would express the opposite desire.

On the basis of the above, α and β levels of .05 were arbitrarily chosen for purposes of determining the required number of control tests. These values state that 5% of the time an erroneous decision may be made regarding the acceptance of poor quality construction and the rejection of satisfactory quality material.

Having established the α and β errors, a value for d (the minimum value at which it is desirable to detect a difference between the sample mean and the population mean) was selected. To correspond with present construction specifications for subgrade and subbase compaction the desired true population mean was taken to be 100 per cent compaction. This assumption states if the hypothesis of equal means is accepted, then the control section is accepted as having a true mean of 100 per cent compaction.

As an example of the above, assume a d value of 5 per cent for both the subgrade and subbase elements. On this basis the hypothesis states that if the sample mean exceeds 95 per cent compaction (true mean of 100% minus d value of 5%) it is not statistically possible to detect the difference between a distribution having this mean and the distribution representing the true population mean 100 per cent compaction.

Recognizing that as a general rule, uniformity of compaction may be more critical for a subbase under a rigid pavement than for the subgrade, d values were selected which placed a tighter control on the subbase compaction level. Values for d of 4% for the subbase and [illegible]% for the subgrade were selected to illustrate the relative importance of the level of compaction control which is required for each element.

The last variable to be established in this analysis was the estimate of variance. To determine this variance estimate, results of the analysis of variance performed for each control section of the individual projects were incorporated. Referring to Table [illegible], the two variance terms involved are the within treatment variance and the between treatment variance where a treatment represents a pair of [illegible] tests. As previously described the within treatment variance (σ_e^2) is primarily due to the testing technique whereas the between treatment variance

[illegible] variability due possibly to different compaction effort, different soil types (different compaction characteristics) and some operator effect as work progressed along the project.

To arrive at a realistic estimate of variance, a combination of the variances was used to account for both replicate testing variance and variability from treatment to treatment. Again referring to Table 2, the following relationship was used to establish the estimate of variance for each control section.

$$\hat{\sigma}^2 = \sigma_e^2 + \sigma_t^2 \qquad (1)$$

where $\hat{\sigma}^2$ = estimate of variance to be used in hypothesis testing

σ_e^2 = replicate testing variance

σ_t^2 = between treatment variance

Having established values for α, β, d and $\hat{\sigma}^2$ a statistical "t" test for the significance of means was used to determine the number of observations required in each control section in order to insure that a given level of quality will be attained. For this study, use was made of Table 9 in the appendix of "Statistics in Research" by B. Ostle (16). To use this table it is neccessary to compute the value of D which is defined as $d/\hat{\sigma}$. Tables 13 and 14 indicates values for n (number of observations required per control section) for each control section studied for the indicated values of α, β, d and $\hat{\sigma}^2$.

An estimate was made of the value of required tests by using the entire project as the control unit. It was found that approximately the same value of n resulted when use was made of an estimate of variance based on the entire project as a control section as was obtained for the average

Table 13

Number (n) of Tests Required Per 2000 ft. Control Section To Insure a Given Level of Quality

Subgrades

($\alpha = \beta = .05 \quad d = 7$)

Section	Project S-1 $\hat{\sigma}$	S-1 D	S-1 n	S-2 $\hat{\sigma}$	S-2 D	S-2 n	S-3 $\hat{\sigma}$	S-3 D	S-3 n
1	6.92	1.01	13	4.50	1.55	7	2.96	2.36	5
2	7.61	.92	15	3.60	1.94	5	3.26	2.14	5
3	7.48	.94	14	7.09	.98	13	6.69	1.08	11
4	3.05	2.29	5	2.36	2.96	5	2.37	2.96	[illegible]
5	4.13	1.69	6	6.21	1.13	11	6.80	1.03	12
6	5.88	1.19	10	6.51	1.07	12	4.44	1.58	6
7	5.50	1.27	9	5.96	1.17	10	3.59	1.95	5
8	5.66	1.24	9	6.60	1.06	12	6.07	1.15	11
9	2.79	2.51	5	5.64	1.24	9	3.48	2.01	5
10	3.00	2.33	5	5.84	1.20	10	4.79	1.46	[illegible]
11	4.29	1.63	6						
Entire Project	5.35	1.31	8	5.76	1.21	9	4.55	1.54	[illegible]
			$\bar{n} = 8.9$			$\bar{n} = 9.4$			$\bar{n} =$ [illegible].2

TABLE 14

Number (n) of Shots Required for 2000 ft. Control Section to Insure a Given Quality

Subbase

(α = β = .05 d = [illegible])

	Project								
	F-[illegible]			F-[illegible]			[illegible]		
Location	$\bar{x}$	s	n	$\bar{x}$	s	n	$\bar{x}$	s	n
1	[illegible]	1.37	[illegible]	-.06	.95	13	2.21	[illegible]	[illegible]
2	[illegible]	2.04	5	-.10	.84	17	1.05	[illegible]	[illegible]
3	[illegible]	1.74	6	1.90	[illegible]	4	1.51	[illegible]	[illegible]
4	[illegible]	[illegible]	10	2.96	[illegible]	4	1.72	[illegible]	[illegible]
5	[illegible]	1.05	11	[illegible]	2.03	[illegible]	[illegible]	[illegible]	[illegible]
6	[illegible]	.81	19	[illegible]	[illegible]	23	1.28	[illegible]	[illegible]
7	[illegible]	1.57	6	[illegible]	3.10	18	[illegible]	1.47	[illegible]
8	[illegible]	1.58	[illegible]	[illegible]	[illegible]	10	[illegible]	[illegible]	[illegible]
9	1.50	[illegible]	[illegible]	[illegible]	[illegible]	6	[illegible]	[illegible]	6
10	[illegible]	1.05	[illegible]	[illegible]	[illegible]	6	[illegible]	[illegible]	5
11				[illegible]	[illegible]	[illegible]			
Entire Project	3.76	[illegible]	10	[illegible]	[illegible]	9	[illegible]	[illegible]	7
		$\bar{n}$ = [illegible]				$\bar{n}$ = 9.5			$\bar{n}$ = [illegible]

of the individual sections indicating that the number of tests required was independent of the size of the control section. (See Tables 13 and 14). A further investigation of this phenomona was made by using a typical subgrade and subbase project and accumulating the variance from section to section and correlating the number of tests required based on these variances with the accumulated length of section. Results of this indicated that the number of tests is independent of the length of control section. These data are shown in Table 15.

The significance of this result is that from a statistical standpoint, decisions concerning quality of construction can be made based on either n tests performed over the entire project or n tests performed in each of a series of control sections. However, insuring an average degree of compaction for the entire project does not imply control over smaller sections within this entire project. *Thus, the major decision to make is "What length of control section should be used to insure uniform performance of the finished product?".*

Table 16 presents a summary of average values of n for the different projects based on different values of d and variance estimates for each individual section. Referring to this table it is possible to select several different values for n which could be employed in a field program of statistical compaction control. The following discussion pertains to several of the alternate choices which can be made.

If it were desired to be conservative and to treat subgrades and subbases equally (same d value), then 15 tests for the subgrades and 7 tests for the subbases would be required. Being less conservative,

[illegible]
[illegible] Length

(a) Project [illegible]

α = [illegible] = .05; d = 5

Section	Obs.	s^2	$\bar{d}^2$	No. of Tests Required	Accumulative Length
1	[illegible]	[illegible]	[illegible]	6	[illegible] feet
1 through 2	10	[illegible]	9.27	[illegible]	4000 feet
1 through 3	[illegible]	3.25	20.[illegible]	13	[illegible] feet
1 through 4	20	[illegible]	16.75	9	[illegible] feet
1 through 5	[illegible]	[illegible]	15.82	[illegible]	[illegible] feet
1 through 6	30	5.35	17.71	[illegible]	12000 feet
1 through 7	[illegible]	[illegible]	18.22	9	[illegible] feet
1 through 8	40	7.93	18.17	10	[illegible] feet
1 through 9	[illegible]	7.60	17.78	10	[illegible] feet
1 through 10	48	12.5[illegible]	20.28	11	20000 feet

(b) Project [illegible]

Section	Obs.	s^2	$\bar{d}^2$	n	Accumulative Length
1	5	4.12	[illegible]	[illegible]	[illegible] feet
1 through 2	10	2.20	6.03	7	[illegible] feet
1 through 3	15	[illegible]	5.57	[illegible]	6000 feet
1 through 4	[illegible]	[illegible]	5.80	5	8000 feet
1 through 5	22	[illegible]	7.3[illegible]	5	10000 feet
1 through 6	27	[illegible]	10.27	5	12000 feet
1 through 7	[illegible]	5.22	10.20	6	14000 feet
1 through 8	[illegible]	[illegible]	7.20	6	16000 feet
1 through 9	41	5.24	[illegible]	[illegible]	18000 feet
1 through 10	[illegible]	6.25	[illegible]	6	20000 feet
1 through 11	[illegible]	6.82	10.[illegible]	7	22000 feet

Table 16

Summary of Tests Required for Each Project
To Insure a Given Quality Level

(a) $\alpha = \beta = .05$
$d = 5$

Subgrades	Subbases
S-1: n = 15	B-1: n = 7
S-2: n = 16	B-2: n = 7
S-3; n = 12	B-3: n = 5

(b) $\alpha = \beta = .05$ $d = 7$ for subgrade
$d = 4$ for subbases

Subgrades	Subbases
S-1; n = 9	B-1: n = 9
S-2; n = 9	B-2: n = 9
S-3; n = 7	B-3: n = 6

It would be possible to choose the smaller values and use 17 and 7 tests respectively. These later values are representative of data obtained using experienced field personnel.

Assuming the subbase is more critical with reference to compaction control and again choosing to be conservative, 9 tests for both elements could be used. (See Table 16 (b)). Again allowing for operator experience, the values for S-3 and B-3 would be applicable since these were the last projects studied and the operators had by that time developed their testing technique. This would result in 7 tests for the subgrade and 6 for the subbase.

Recent developments in highway construction indicate that the use of nuclear moisture-density gages for determining field density is gaining favor among highway engineers. The operator term that is associated with the establishment of the variance estimate would be minimized for these gages. Thus, by being able to reduce the magnitude of the variance term, the number of field tests required could also be decreased. The data of this study do not indicate the magnitude of reduction that would be allowed. It would seem that the use of the values for the number of tests required corresponding to the variance estimate associated with experienced field personnel would be applicable to these gages.

Values of n were also determined for the subgrades using the variance terms obtained by analyzing the project on the basis of equivalent soil type control sections. However, this approach did not appreciably change the number of tests required as might be expected since the variable of soil type was removed (see Table 17)

Table 17

A Comparison of the Number (n) of Tests Required for Control Sections Based on Constant Size Versus Those Based on Uniform Soil Types

Project S-3

$\alpha = \beta = .05 \quad d = 5$

a) Constant Size Control Section			b) Uniform Soil Type Control Section		
Tests Involved	Variance Estimate ($\hat{\sigma}^2$)	Number of Tests Required	Tests Involved	Variance Estimate ($\hat{\sigma}^2$)	Number of Tests Required
1-5	8.78	6	4,5	34.[illegible]	17
6-10	10.68	7	1,3	0.[illegible]	5
11-15	42.44	20	6-10	10.03	6
16-20	5.66	5	11-15	50.[illegible]	24
[illegible]	46.50	21	17,19	55.[illegible]	26
21-25	19.87	11	16,18,20;46-50	21.[illegible]	12
31-35	12.96	5	21,22,24	19.[illegible]	11
36-40	37.05	18	23,25;31-35:37-39	28.[illegible]	16
41-44	12.20	8	27,28,36,41,43,44	25.[illegible]	13
45-50	23.06	12	26,29,30	[illegible]	10
Overall	20.72	11	Overall	24.02	13

Limit of accuracy curves, using the overall estimate of varian e previously determined for the different sites, were developed for each project. These curves are based on the relationship:

$$L = \pm t_{\left[\left(1 - \alpha/2 \right),\ \nu \right]} \sqrt{\hat{\sigma}^2 / n} \qquad (2)$$

Where L = Limit of accuracy

ν = Degrees of freedom

n = Number of observations

$\hat{\sigma}^2$ = Estimate of variance

α = Confidence level (α = .05 was used for purposes of computing L)

t = Value from t table for given α and ν

Figure 27 shows the limit of accuracy curves for all six projects investigated. As an example of the use of these curves, assume that 10 tests per 2,000 ft. section are specified and that to be conservative, curves for S-2 and B-1 are taken as being valid for the two general elements studied. Using these data, the average per cent compaction of 10 subbase tests would be within ± 2.3% of the true mean of the section 95% of the time for the subbases. This value would be ± 4.1% for the subgrades. Again assuming 10 tests but also assuming experienced operators, curves S-3 and B-3 are applicable for subgrades and subbases respectively. This would result in limits of accuracy of ± 1.6% for the subbase and ± 3.3% for the subgrade.

The data indicate that the final decision as to the number of field observations required per control section depends on a number of factors. It is important to recognize that variability does exist and that various factors including soil type, compaction technique and precision of the technician are interrelated in causing this variability.

In looking at the overall range in data, it appears that many observations obtained in this study were well below what would normally be termed "satisfactory compaction." Therefore, in applying quality control to a project, it would be most desirable to set an absolute minimum lower limit of per cent compaction. The magnitude of this lower compaction limit cannot be ascertained from the data of this study. The use of such a lower control limit would no doubt change the distributions that were observed in this particular study from a normal distribution to some other distribution. It is not possible to estimate the effect of this change on the data but it should be recognized since it could negate many of the observations and results obtained in this particular study.

Data collected in this study have demonstrated that there are many factors which effect variability of compaction of subbases and subgrades. It has been most difficult to separate the variables and to determine the relative effect of each. However, there is no doubt that considerable variation in compacted density existed in the finished product and the data have demonstrated forcibly the fallicy of performing just one or two tests in a given section of road for control purposes. The results of this study have further demonstrated the need for future research into several areas such as the determination of the optimum size of control section, the determination of the number of tests required per section, the average density to be obtained from these tests and the effect of various factors which influence compaction variability.

SUMMARY OF RESULTS

Comparison of Testing Procedures and Results

1. A comparison between the results obtained using a field one-point compaction test along with a family of typical compaction control curves to obtain maximum subgrade density values, and results from standard laboratory compaction data indicated that the two techniques are compatible. Results of the field one-point tests averaged 3 pcf lower than laboratory data.
2. Moisture contents determinded by drying the material on a field stove and those determined by drying in the laboratory indicated that approximately 92% of these tests checked with ± 2 percentage points of moisture content. Factors affecting these results were the operator performing the field test and types of material.
3. The tests indicated that results of laboratory washed sieve analysis and field dry sieve analysis were compatible for the three sieves studied (3/4", No. 4 and No. 10).
4. Calibration of density sand in a steel mold of known volume yielded values essentially the same as opposed to weighing the sand in the sand cone jug itself. The average difference in sand density as determined by these two techniques was 0.6 pcf.

Comparison of Methods for Determining Maximum Density and Per Cent Compaction

1. Control curves relating the per cent of material passing a No. 4 sieve and maximum dry density were developed for each subbase project. Use of these curves permitted the determination of maximum dry density for each field density test thus accounting for material

variability. It was found for the subbase projects in this study, use of an average maximum density value gave essentially the same results as those from the control curves. This, however, would not be true of all subbase materials.

2. Two basic techniques for determining appropriate maximum density values for subgrade soils were studied. These were (a) use of an average density value for different soil groups as defined by laboratory classification and compaction tests and (b) use of a field one-point compaction test in conjunction with a family of typical compaction curves. The first technique mentioned does not, in general, appear feasible for field use since an accurate determination of liquid limit for each soil is required. However, if the project engineer is supplied with the appropriate equipment to perform the necessary tests, this method has some promise. Use of visual inspection for classification and choosing the correct compaction curve is suspect unless done by experienced personnel. The results of this study indicate that the most realistic technique for determining maximum density for subgrades is to make use of a field one-point compaction test. The suggestion is made that a set of compaction control curves can be developed for each project. The one-point technique permits the field personnel to determine a maximum density value for each in-place density test and thereby accounts for soil variability.

3. Results of tests from one project which was tested soon after final compaction indicated very close agreement between per cent compaction values computed on both a wet and dry densities basis. For projects tested after a period of time had elapsed after compaction, per cent compaction on a dry basis was greater than the corresponding value on a wet basis.

Variability Observed

1. The per cent compaction data was observed to be normally distributed for all sites studied. Average per cent compaction values and the range in values for each project based on maximum dry density values obtained using the one-point compaction tests for the subgrades and the control curves for the subbase were:

Project	Average Per Cent Compaction	Range in Per Cent Compaction	Standard Deviation
S-1	100.6	84 - 116	5.5
S-2	96.8	80 - 110	5.7
S-3	98.2	84 - 108	4.5
B-1	89.4	82 - 98	3.3
B-2	91.7	84 - 100	3.1
B-3	93.6	86 - 100	2.3

2. Material variability was quite pronounced for the subgrade soils and less so for the subbase material. Families of compaction curves which were developed for each subgrade site resulted in a range in maximum dry density values of approximately twenty pounds per cubic foot for each project.
   Five basic soil groups were defined for the subgrades tested. These groups were repeated from project to project and the distribution of these soil groups along a project was noted to be random in nature.

3. For this study, the variability found in the subbase materials (grain size variation) did not have a critical effect on the determination of maximum dry density values.

Factors Influencing Variability Observed

1. An analysis of variance indicated that the project itself had an influence on the results and thus each project was studied as an individual construction item rather than on the basis of subgrade or subbase elements in general.
2. Variability within each project was investigated by analyzing the individual control sections which contained approximately 5 treatments (a treatment represents replicate tests). Compaction from one section to another on a project was observed to vary widely for all sites studied. Also, compaction within a section was found to vary considerably for some units whereas it was relatively constant throughout other sections.
3. General material type, subbase or subgrade, showed a distinct difference in variability observed. Much more consistent results were obtained for the subbase materials in comparison to the subgrades. Both types of variation studied, section to section and within a section, were more pronounced for the subgrades than for the subbases. Average differences between replicate in-place density tests were much larger for the subgrade projects than they were for the subbases. Much of this is attributed to the difficulty of performing the field density test in the subgrade materials and to the wider variations in soil type observed for the subgrades.

For the different subgrade soils investigated, soil type appeared to influence the compaction results. As soil plasticity increased and maximum density decreased, per cent compaction increased. This phenomena was observed to be a general effect. Also, compaction for two given soil types which were represented on each site was approximately the same regardless of project or contractor.

4. The influence of testing personnel on the overall variance was determined by studying the within treatment variance terms which are primarily an indication of testing variance. This term decreased as the testing progressed indicating that as the field personnel gained experience and established their technique the associated testing variation decreased. This was especially true for tests on the subbase and less so for the subgrades. The difference between the subgrade and subbase was attributed primarily to the wide compaction variability observed for the subgrade soils and the difficulty in testing them in comparison to the subbase materials. Thus, the effect of material type tended to interact with the effect of operators for the subgrades and confuse the interpretation of the results concerning the magnitude of variance attributable to each. A comparison of various operators indicated that different variations were associated with individual personnel.
5. The interactions of the effects due to different material types, different operators and different contractors or projects cause the overall variation to be random in nature.

Typical Guidelines for Statistical Quality Control Program

1. The size of control section which should be tested to provide an estimate of the overall compaction level may be established by several techniques. The most realistic of these appears to be to define sections of a given area or volume and divide a project into units of constant size, irrespective of material type. The size of the section, however, is critical and the results of this study shed no light on what the optimum size should be. The need for additional work on this phase is indicated.
2. The number of tests required to predict average degree of compaction for a given section depends upon many variables. The number of required tests was found to be independent of length of section. From the results of this study, the required number of tests varied widely but; on the average, between 5 and 16 tests are required per section depending on the element involved. The final choice of this value must be based on a study of performance of highways in service. The critical factor, however, of length of section to consider must be resolved by future work before adequate decisions can be made.
3. The average per cent compaction value that the specified number of tests must exceed also needs to be delineated. This in turn has an influence on the number of tests required. This value must be based on performance studies along with an understanding of the influence that this value will have on the overall statistical control program.

4. Based on the wide overall range in per cent compaction observed in this study it appears that an absolute lower limit should be specified such that a section would not be accepted if a single test fell below this value. This statement is predicated on the assumption that, irrespective of the *average* density, localised failure will result if certain minimum conditions are not met.

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Table A-1

Analysis of Variance-Nested Model
Subgrades

Source of Variation	df	ss	ms	F
Projects	2	840.6	420.3	8.3
Treatment Within Project	47	2028.4	43.2	0.84
Error	238	5488.1	51.0	

$F_{.05;\ 2,238} = 3.04 < 8.3$ ∴ Project is significant

$F_{.05;\ 47,238} = 1.37 > .84$ ∴ Treatment with project is not significant

Table A-2

Analysis of Variance-Nested Model
Subbases

Source of Variation	df	ss	ms	F
Projects	2	861.9	431.0	23.5
Treatment Within Project	49	496.7	10.1	0.55
Error	248	2024.7	18.3	

$F_{.05;\ 2,248} = 3.04 < 23.5$ ∴ Project is significant

$F_{.05;\ 49,248} = 1.35 > 0.55$ ∴ Treatment within project is not significant

Table [illegible]

One-Way ANOV Results for [illegible]
(Per Cent [illegible]
Compaction Test [illegible])

Source of Variation	[illegible]	[illegible]	[illegible]	[illegible]
<u>S-1</u>				
Means	50	2149.3	[illegible]	[illegible]
Within Treatments	51	740.1	14.5	
$F_{.05;\ 50,51}$ = 1.[illegible] < [illegible]		Between treatments is [illegible]		
<u>S-2</u>				
Means	47	2285.7	48.6	[illegible]
Within Treatments	48	773.6	16.1	
$F_{.05;\ 47,48}$ = 1.[illegible] < 3.0[illegible]		Between treatments is [illegible]		
<u>S-3</u>				
Means	46	1329.2	28.9	[illegible]
Within Treatments	47	596.4	12.[illegible]	
$F_{.05;\ 46,47}$ = 1.63 < 2.2[illegible]		Between treatments is significant		

Table A-4

One-Way ANOV Results for Subbase Projects
(Per Cent Compaction Based on Control
Curve Maximum Dry Densities)

Source of Variation	df	ss	ms	F
B-1				
Means	50	706.2	14.2	2.1
Within Treatments	51	346.3	6.8	
$F_{.05;\ 50,51} = 1.60 < 2.1$ ∴ Between treatments is significant				
B-2				
Means	54	800.9	14.8	3.4
Within Treatments	55	243.1	4.4	
$F_{.05;\ 54,55} = 1.89 < 3.4$ ∴ Between treatments is significant				
B-3				
Means	49	385.3	7.9	3.0
Within Treatments	50	130.1	2.6	
$F_{.05;\ 49,50} = 1.60 < 3.0$ ∴ Between treatments is significant				

Table A-5

Summary of Variance Data for
the Field Control Sections

Subgrades

Section*	Project S-1 Within Treatment Variance	Project S-1 Between Treatment Variance	Project S-2 Within Treatment Variance	Project S-2 Between Treatment Variance	Project S-3 Within Treatment Variance	Project S-3 Between Treatment Variance
1	5.24	49.94	20.29	---	1.70	7.07
2	10.06	48.02	5.99	7.07	4.84	5.84
3	56.15	---	25.10	24.51	1.98	40.46
4	9.38	---	2.07	3.54	3.04	2.62
5	17.14	---	8.67	30.14	55.16	---
6	4.33	10.17	6.09	36.55	46.50	---
7	6.74	23.66	15.10	20.64	5.90	13.98
8	22.38	9.82	43.78	---	12.96	---
9	7.81	---	8.26	23.64	18.36	18.70
10	4.18	4.85	21.96	12.45	3.25	8.95
11	12.17	6.31	---	---	13.43	9.63

Subbases

Section*	Project B-1 Within Treatment Variance	Project B-1 Between Treatment Variance	Project B-2 Within Treatment Variance	Project B-2 Between Treatment Variance	Project B-3 Within Treatment Variance	Project B-3 Between Treatment Variance
1	4.32	4.20	5.93	10.84	0.68	4.24
2	1.28	2.53	5.29	17.46	1.96	7.39
3	3.47	1.84	7.68	0.76	1.12	1.25
4	3.13	7.68	8.80	---	3.13	4.73
5	3.43	11.18	2.65	3.39	2.89	1.72
6	20.50	4.00	0.75	11.84	1.27	0.65
7	0.59	5.95	7.17	7.69	3.31	1.29
8	2.39	4.90	3.29	7.86	1.23	4.03
9	5.76	0.94	2.52	3.34	4.31	0.75
10	14.70	---	0.17	5.19	1.65	0.88
11	12.07	0.33	1.93	1.21	---	---

Note: Sections are arbitrarily numbered and represent sections of material approximately 2000 feet in length having five replicate tests performed each section. There is no particular correlation between Section 1 of Project S-1 and Section 1 of any of the other projects.

Table A-6

Average Percent Subgrade Compaction
for Field Control Sections

Project	Station	Lane	Percent Compaction *
S-1	420+00 - 450+00	SB	96.9
	450+00 - 480+00	SB	97.8
	480+00 - 510+00	SB	101.2
	510+00 - 540+00	SB	99.1
	540+00 - 570+00	SB	100.5
	570+00 - 600+00	SB	104.1
	600+00 - 630+00	SB	100.5
	630+00 - 660+00	SB	102.7
	660+00 - 690+00	SB	105.0
	690+00 - 720+00	SB	103.4
	560+00 - 580+00	NB	95.6
S-2	45+00 - 214+00	WB	98.3
	214+00 - 235+00	WB	96.8
	235+00 - 255+00	WB	91.9
	255+00 - 274+00	WB	94.3
	191+00 - 211+00	WB	100.3
	211+00 - 233+00	WB	100.6
	233+00 - 253+00	WB	97.6
	186+00 - 206+00	EB	94.5
	206+00 - 226+00	EB	97.5
	226+00 - 246+00	EB	96.0
S-3	1100+00 - 1120+00	WB	98.8
	1120+00 - 1140+00	WB	97.6
	1170+00 - 1190+00	WB	98.5
	1190+00 - 1210+00	WB	99.6
	1230+00 - 1250+00	WB	99.4
	1030+00 - 1050+00	EB	94.2
	1050+00 - 1070+00	EB	99.8
	1070+00 - 1090+00	EB	100.8
	1090+00 - 1110+00	EB	97.5
	1110+00 - 1130+00	EB	96.2

* Based on One-Point Compaction Test

Table A-7

Average Subgrade Percent Compaction Values
Based on Soil Groups

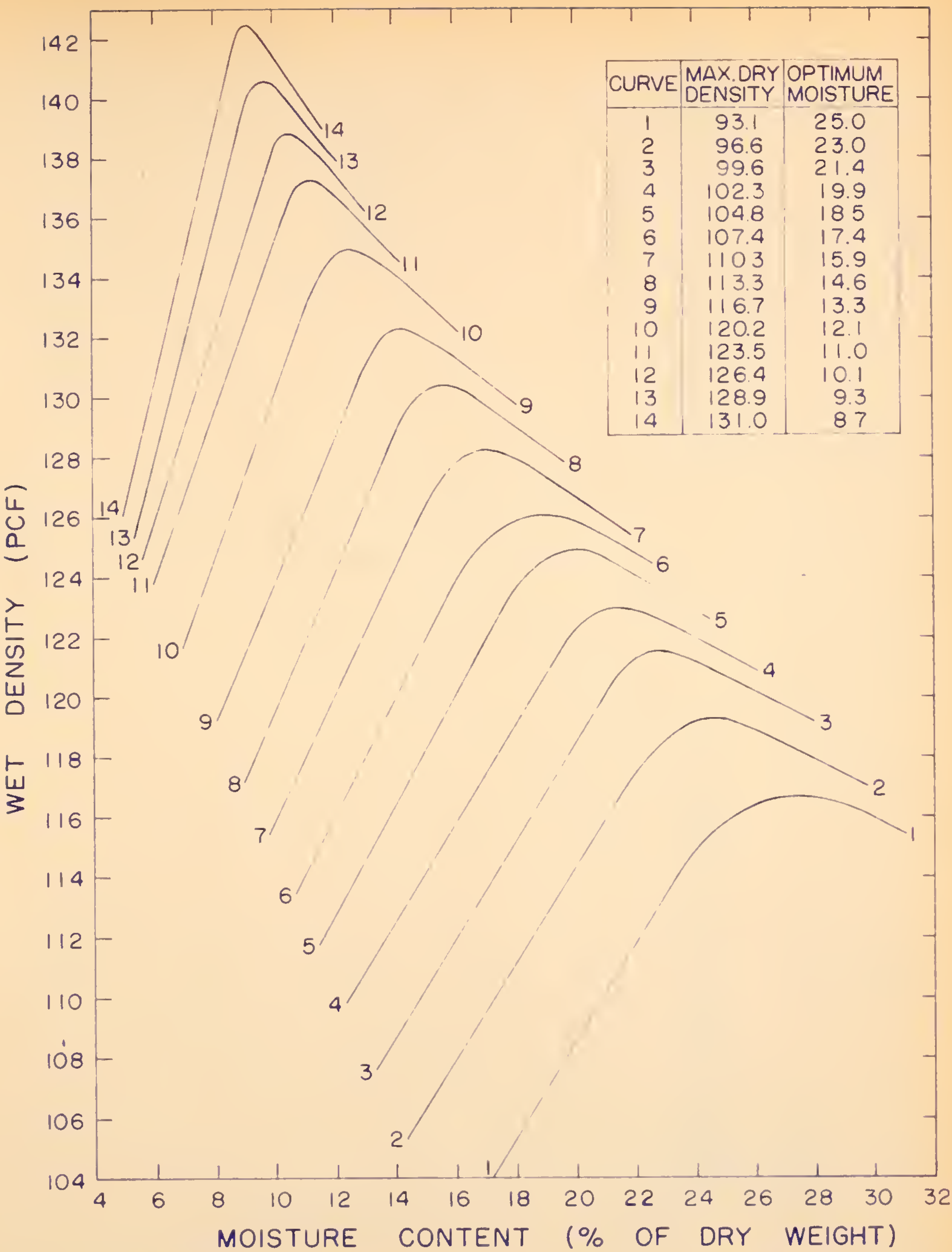
Project	Station	Lane	Soil Group	Average Percent Compaction *
S-1	420+00 - 440+00	SB	C	95.2
	440+00 - 448+00	SB	B	88.5
	448+00 - 470+00	SB	C	95.2
	470+00 - 480+00	SB	D	95.1
	480+00 - 540+00	SB	C	94.9
	540+00 - 570+00	SB	D	97.3
	570+00 - 584+00	SB	C	99.1
	584+00 - 586+00	SB	B	98.6
	586+00 - 604+00	SB	C	100.3
	604+00 - 610+00	SB	D	98.0
	610+00 - 644+00	SB	C	97.4
	644+00 - 650+00	SB	B	95.6
	650+00 - 657+00	SB	C	104.8
	657+00 - 690+00	SB	D	99.5
	690+00 - 692+00	SB	E	102.5
	692+00 - 700+00	SB	C	99.6
	700+00 - 706+00	SB	E	103.2
	706+00 - 720+00	SB	C	95.5
	560+00 - 568+00	NB	C	91.9
	568+00 - 570+00	NB	D	102.1
	570+00 - 580+00	NB	B	97.6
S-2	45+00 - 234+00	WB	B	93.0
	234+00 - 250+00	WB	A	89.8
	250+00 - 274+00	WB	B	90.8
	191+00 - 202+00	WB	C	105.4
	202+00 - 238+00	WB	B	92.8
	238+00 - 252+00	WB	A	94.0
	252+00 - 260+00	WB	C	103.2
	190+00 - 203+00	EB	B	95.1
	203+00 - 205+00	EB	C	92.6
	205+00 - 206+00	EB	A	95.0
	206+00 - 240+00	EB	B	98.7
	240+00 - 246+00	EB	A	92.0
S-3	Data for this project are shown on Figure 23			

* Based on Soil Group Average Maximum Dry Density

Table A-8

Comparison of Within Treatment Variance
Data for Different Operator Combinations

Subgrades			
Project	Operators	Number of Replicate Tests Involved	Within Treatment Variance
S-1	1,5,6	4	2.07
S-1	3,5	4	12.17
S-1	1,3	12	9.49
S-1	2,4	13	16.37
S-1	5,6	18	19.81
S-2	2,5,6	4	1.80
S-2	5,6	21	12.44
S-2	1,2	24	21.25
S-3	2,3	48	12.92
Subbases			
B-1	2,4	52	6.79
B-2	3,4,5	29	3.05
B-2	1,4	20	7.16
B-2	3,4	5	0.75
B-3	2,3	3	2.46
B-3	2,3,6	4	5.28
B-3	3,4	20	1.72
B-3	5,6	23	1.95



CURVE	MAX. DRY DENSITY	OPTIMUM MOISTURE
1	93.1	25.0
2	96.6	23.0
3	99.6	21.4
4	102.3	19.9
5	104.8	18.5
6	107.4	17.4
7	110.3	15.9
8	113.3	14.6
9	116.7	13.3
10	120.2	12.1
11	123.5	11.0
12	126.4	10.1
13	128.9	9.3
14	131.0	8.7

FIGURE 1 FAMILY OF TYPICAL INDIANA MOISTURE DENSITY CURVES (FROM SPENCER)

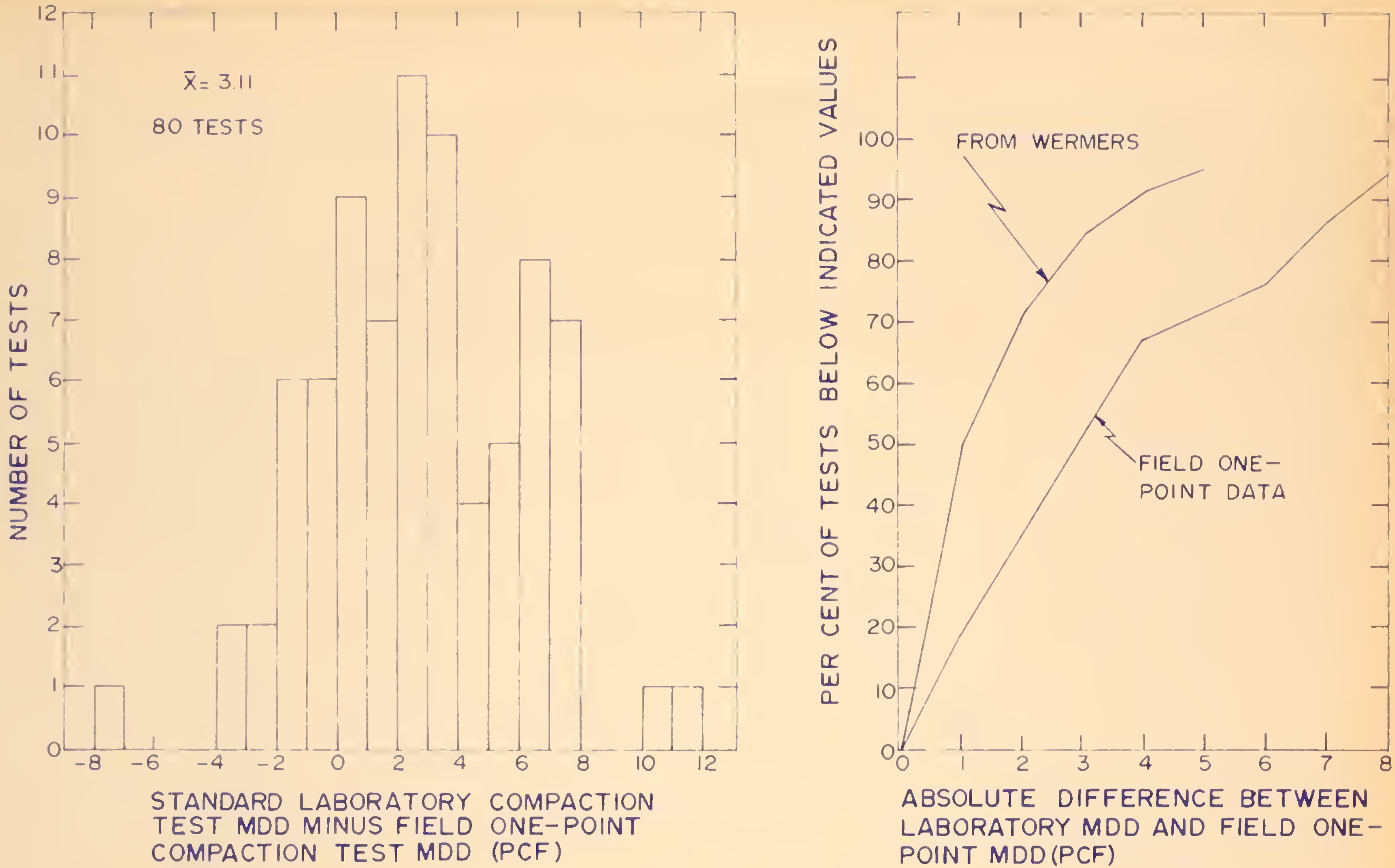


FIGURE 2 FREQUENCY HISTOGRAM AND CUMULATIVE POLYGON INDICATING DIFFERENCE BETWEEN STANDARD LABORATORY COMPACTION TEST MAXIMUM DRY DENSITY AND FIELD ONE-POINT COMPACTION TEST MAXIMUM DRY DENSITY.

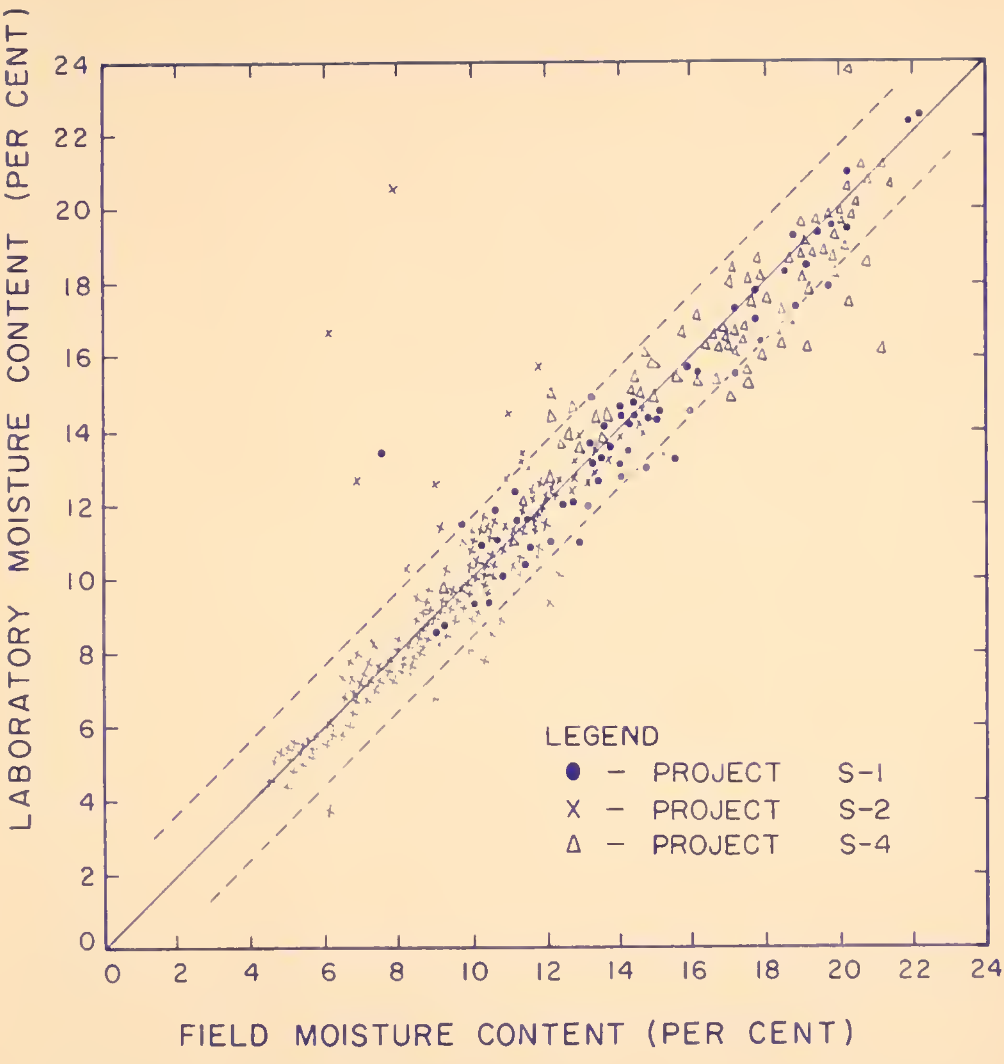


FIGURE 3 COMPARISON OF LABORATORY AND FIELD DETERMINED MOISTURE CONTENTS FOR SUBGRADES

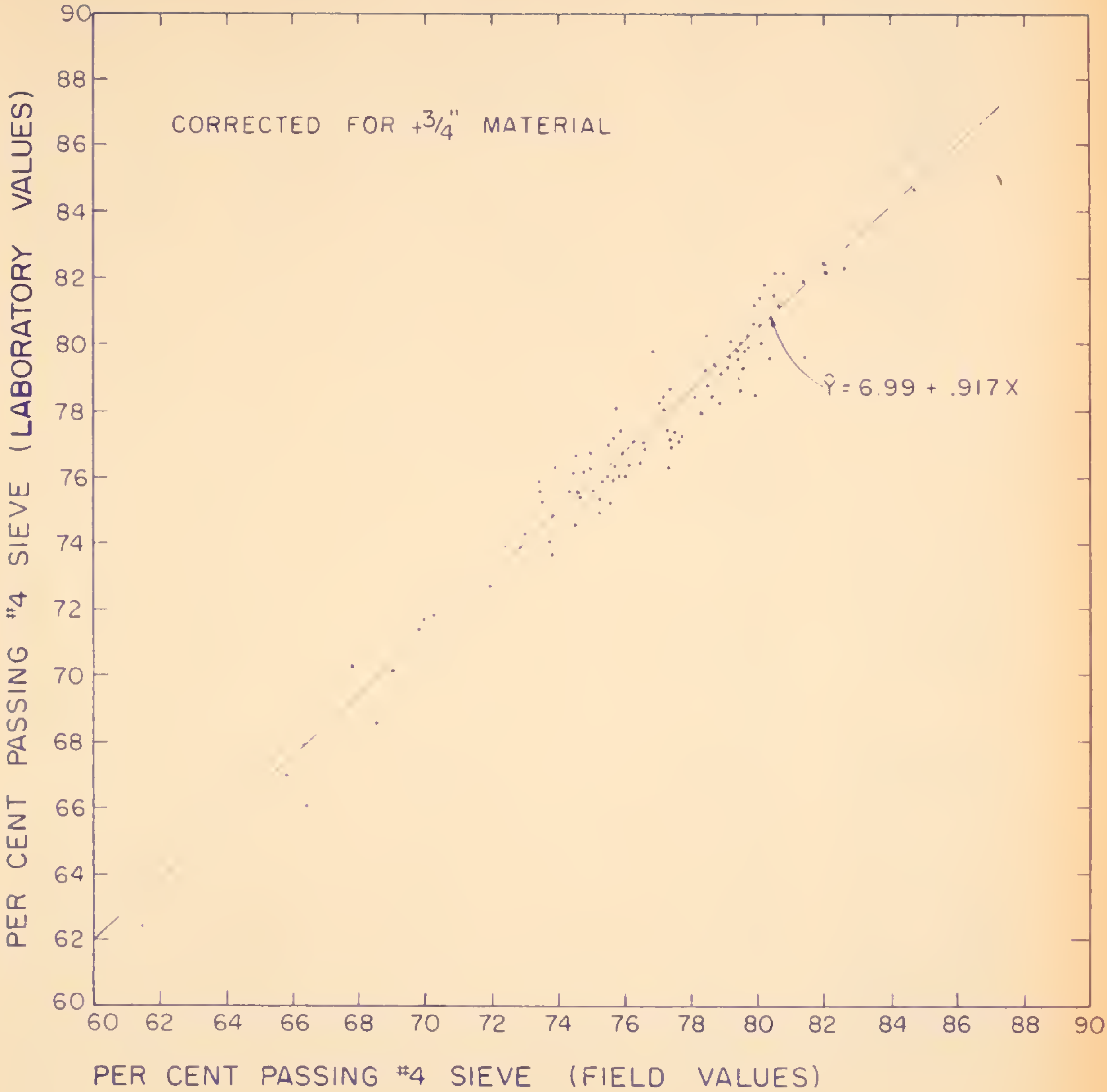


FIGURE 4 FIELD vs. LABORATORY SIEVE ANALYSIS FOR #4 SIEVE (SUBBASE MATERIAL FROM PROJECT B-1)

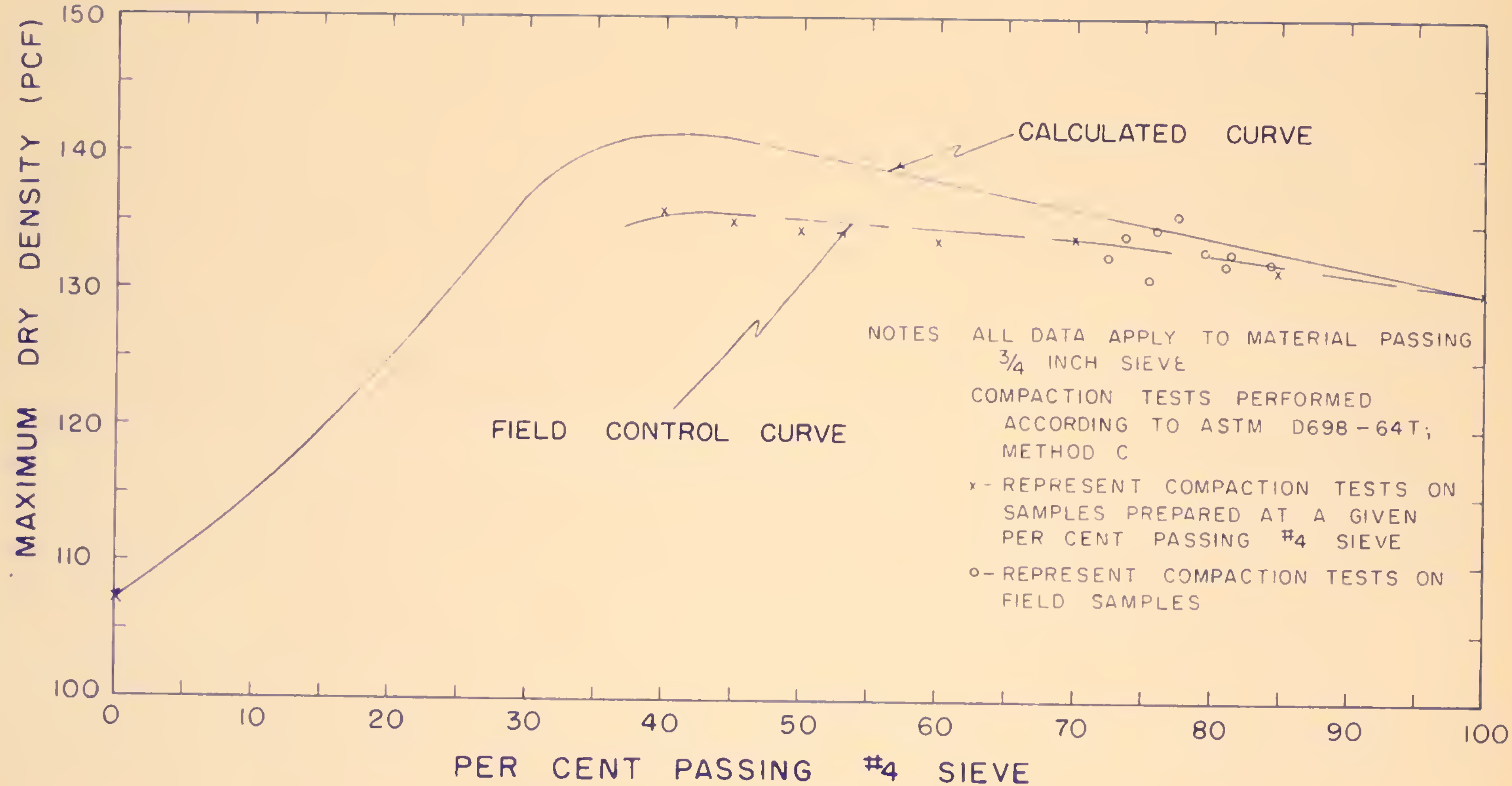


FIGURE 5 CURVES SHOWING VARIATION OF MAXIMUM DRY DENSITY WITH PER CENT PASSING A #4 SIEVE (SUBBASE MATERIAL FROM PROJECT B-1)

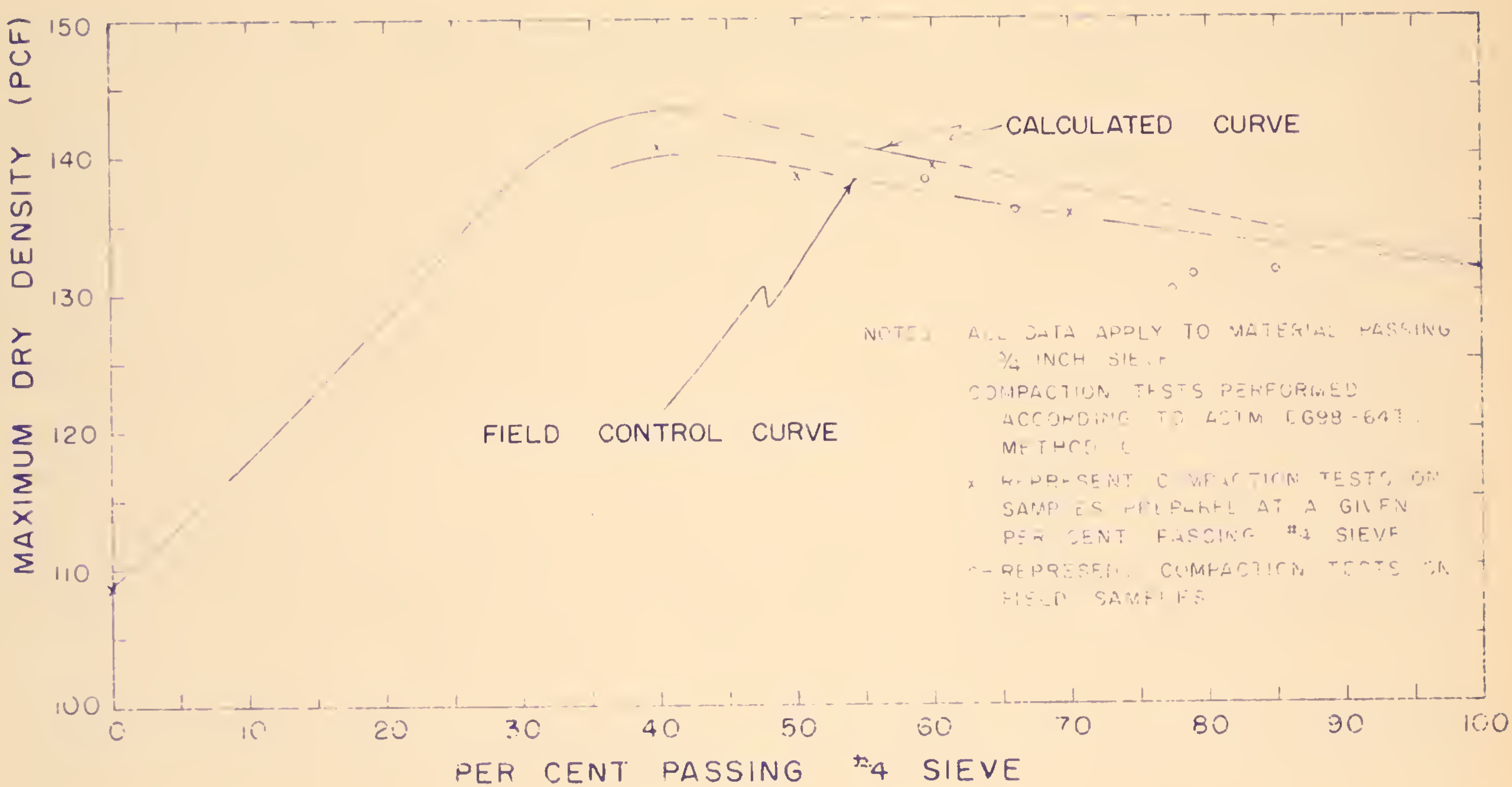


FIGURE 6 CURVES SHOWING VARIATION OF MAXIMUM DRY DENSITY WITH PER CENT PASSING A #4 SIEVE (SUBBASE MATERIAL FROM PROJECT B-2)

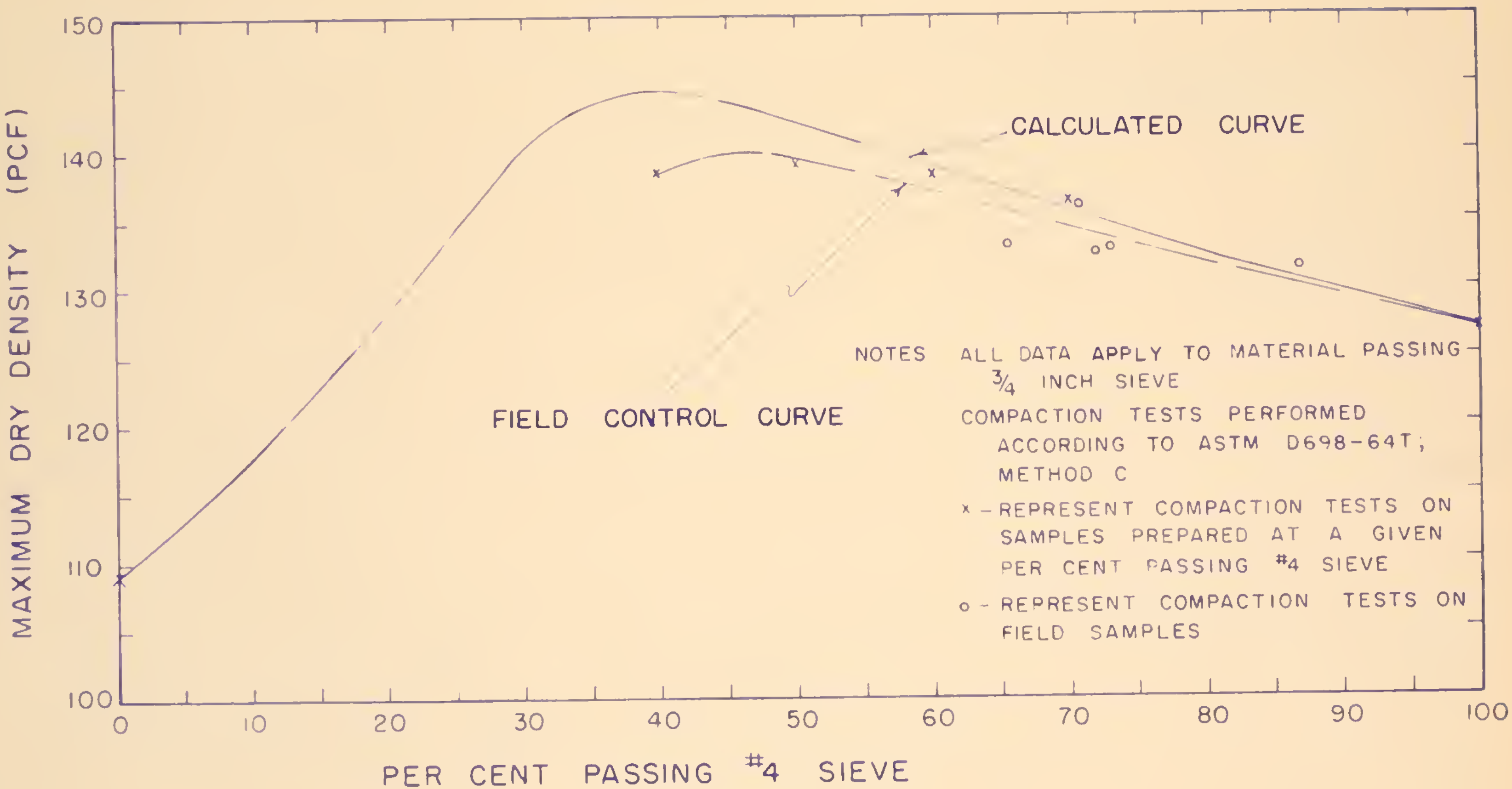


FIGURE 7 CURVES SHOWING VARIATION OF MAXIMUM DRY DENSITY WITH PER CENT PASSING A #4 SIEVE (SUBBASE MATERIAL FROM PROJECT B-3)

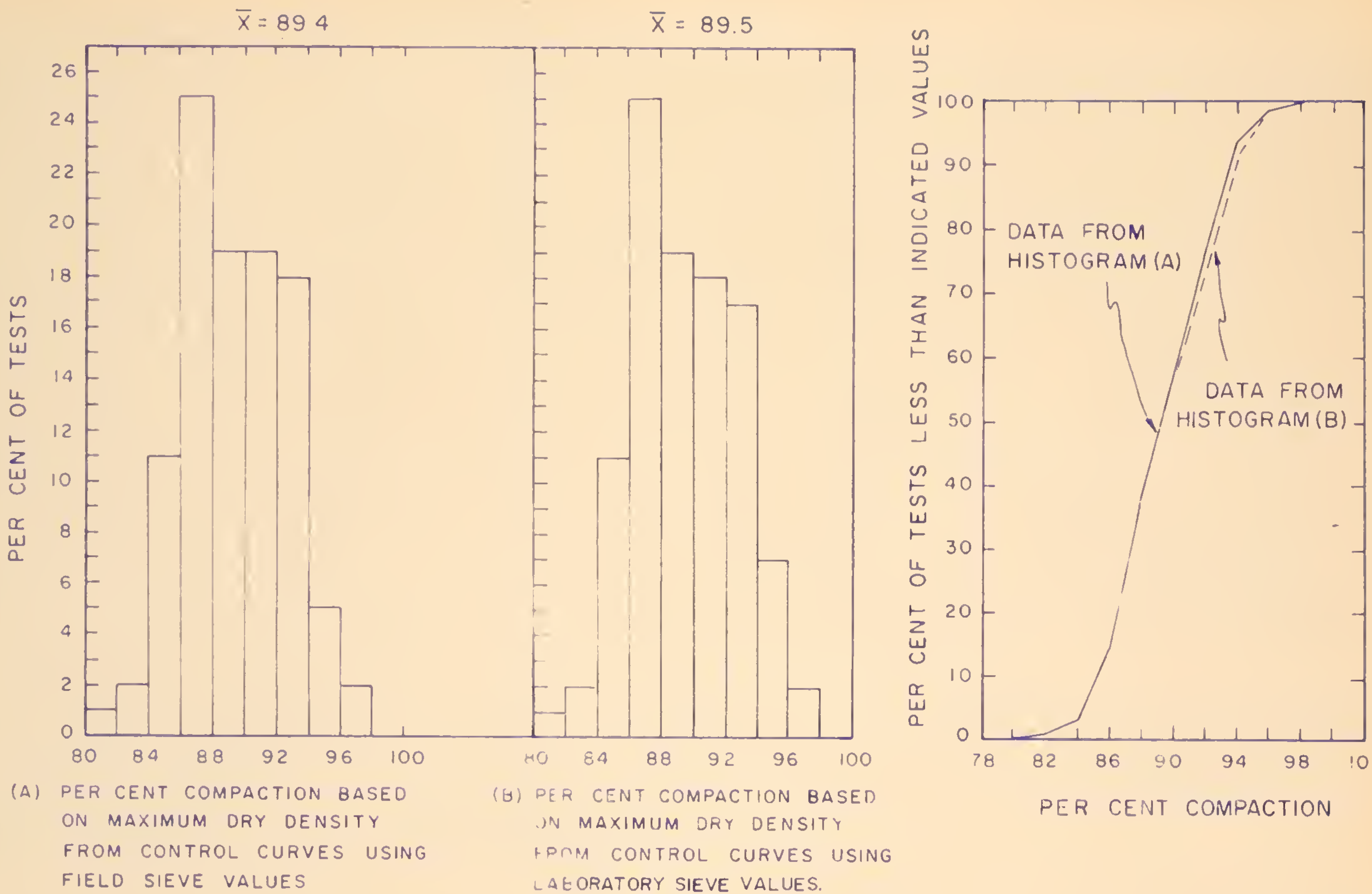
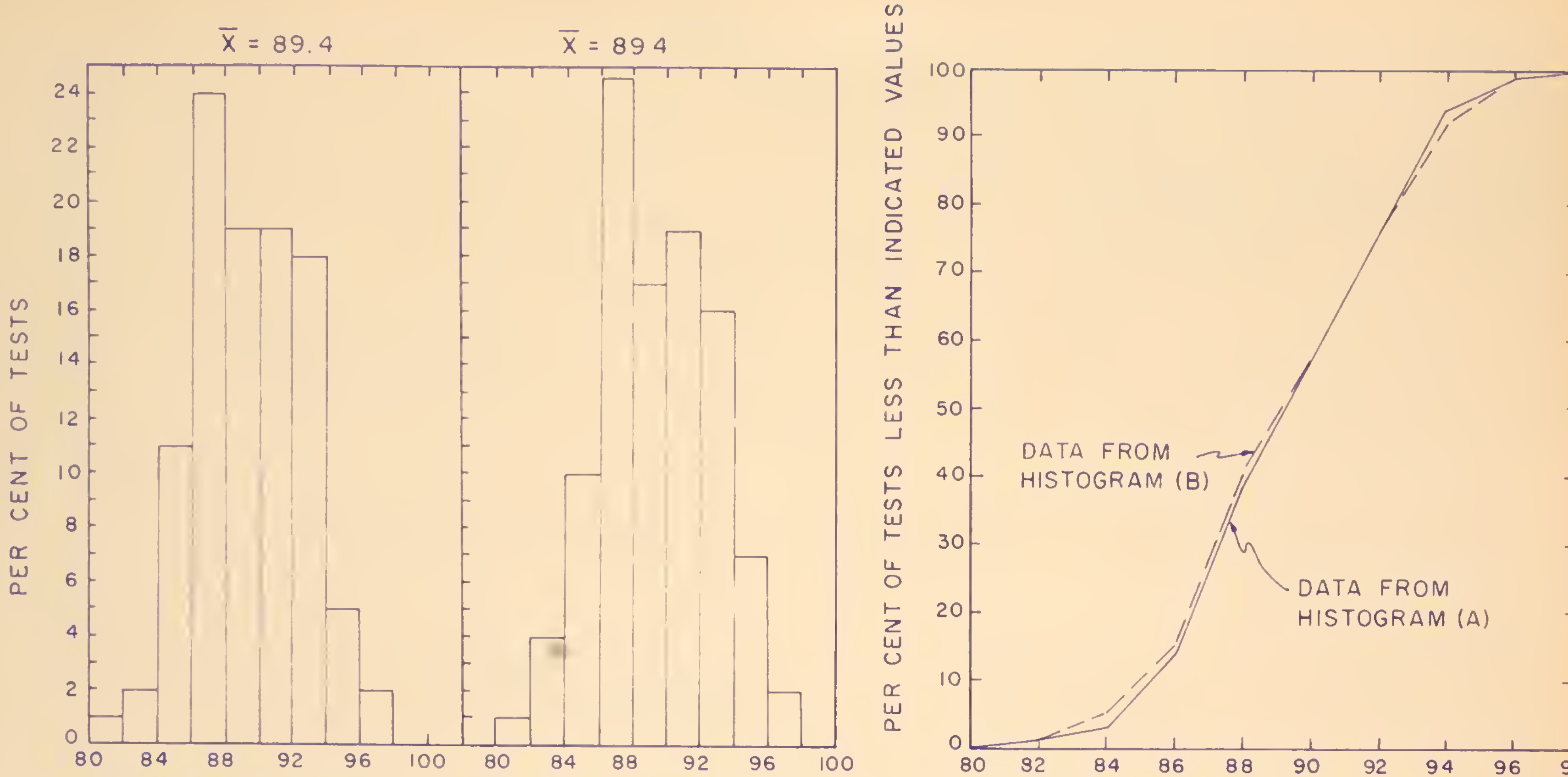


FIGURE 8 COMPARISON OF TWO TECHNIQUES FOR COMPUTING PER CENT COMPACTION (SUBBASE MATERIAL FROM PROJECT B-1)



(A) PER CENT COMPACTION BASED ON MAXIMUM DRY DENSITY FROM CONTROL CURVE USING FIELD SIEVE VALUES

(B) PER CENT COMPACTION BASED ON AVERAGE MAXIMUM DRY DENSITY FROM CONTROL CURVE FOR FIELD SIEVE VALUES

FIGURE 9 COMPARISON OF TWO TECHNIQUES FOR COMPUTING PER CENT COMPACTION (SUBBASE MATERIAL FROM PROJECT B-1)

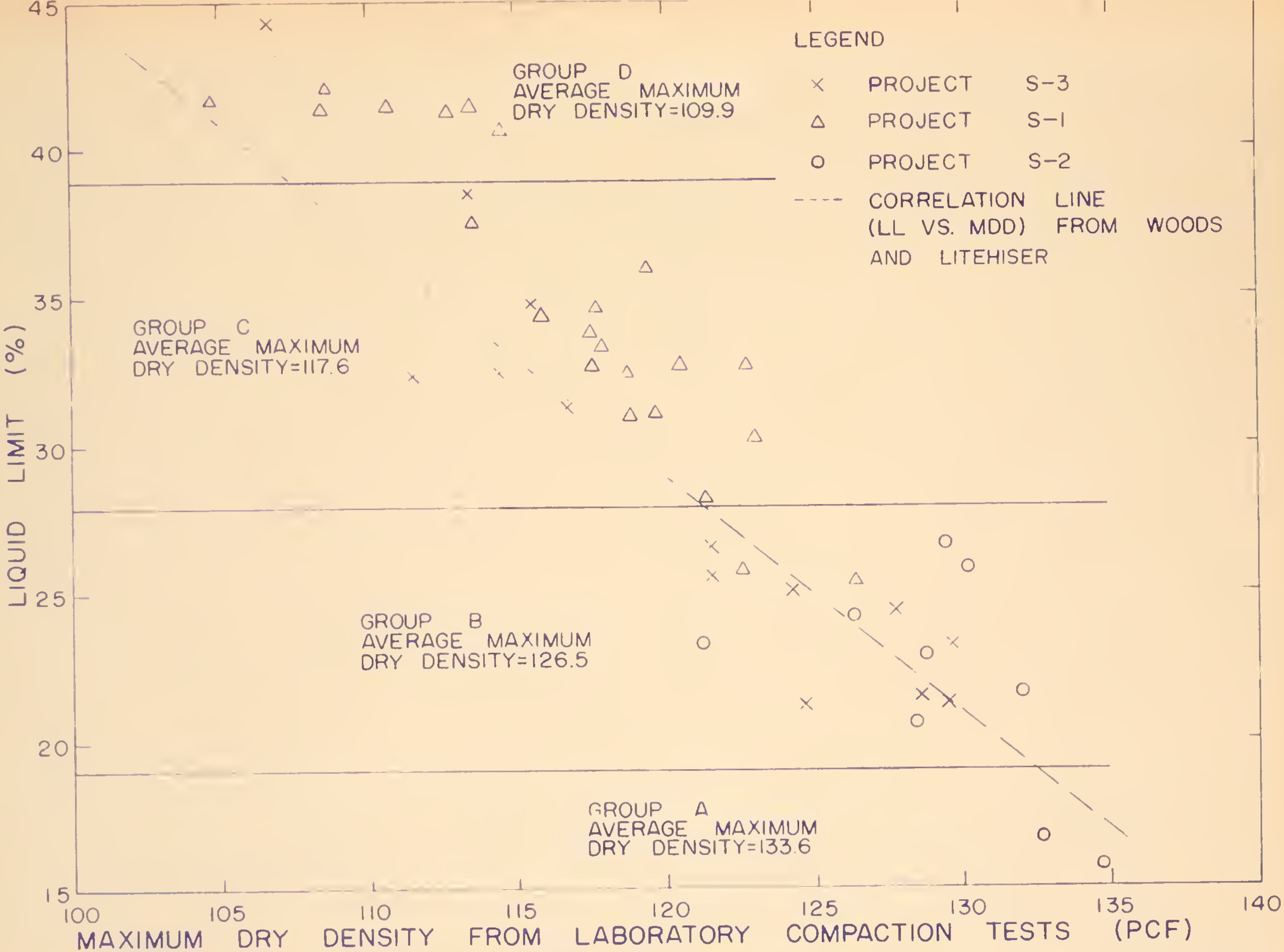


FIGURE 10 LIQUID LIMIT vs. MAXIMUM DRY DENSITY FOR SOIL SAMPLES FROM THREE SUBGRADE PROJECTS SHOWING ASSUMED SOIL CLASSIFICATION GROUPS AND AVERAGE MAXIMUM DRY DENSITIES

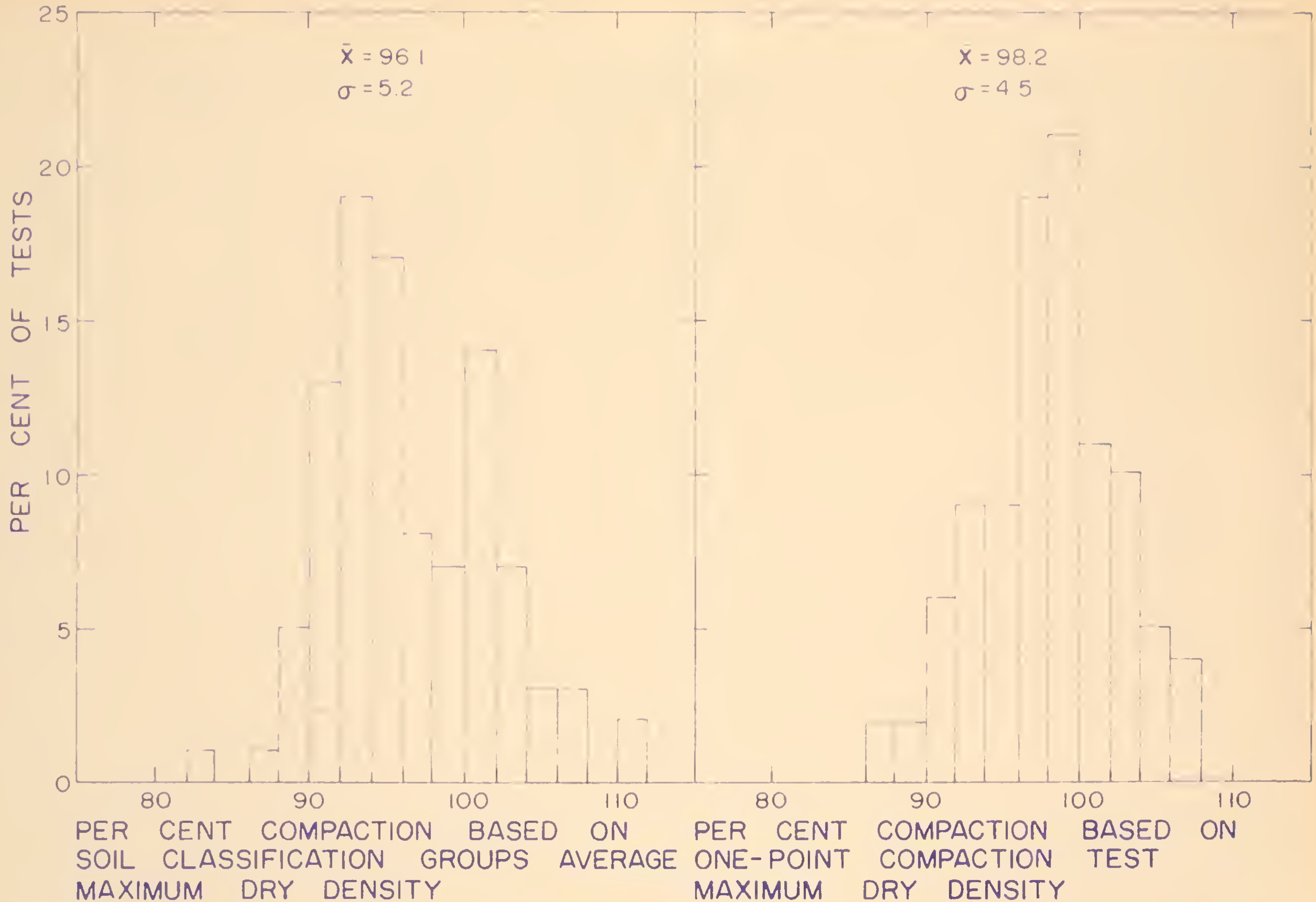


FIGURE 11 FREQUENCY HISTOGRAMS OF SUBGRADE PER CENT COMPACTION BASED ON TWO DIFFERENT TECHNIQUES FOR DETERMINING MAXIMUM DRY DENSITIES (PROJECT S-3)

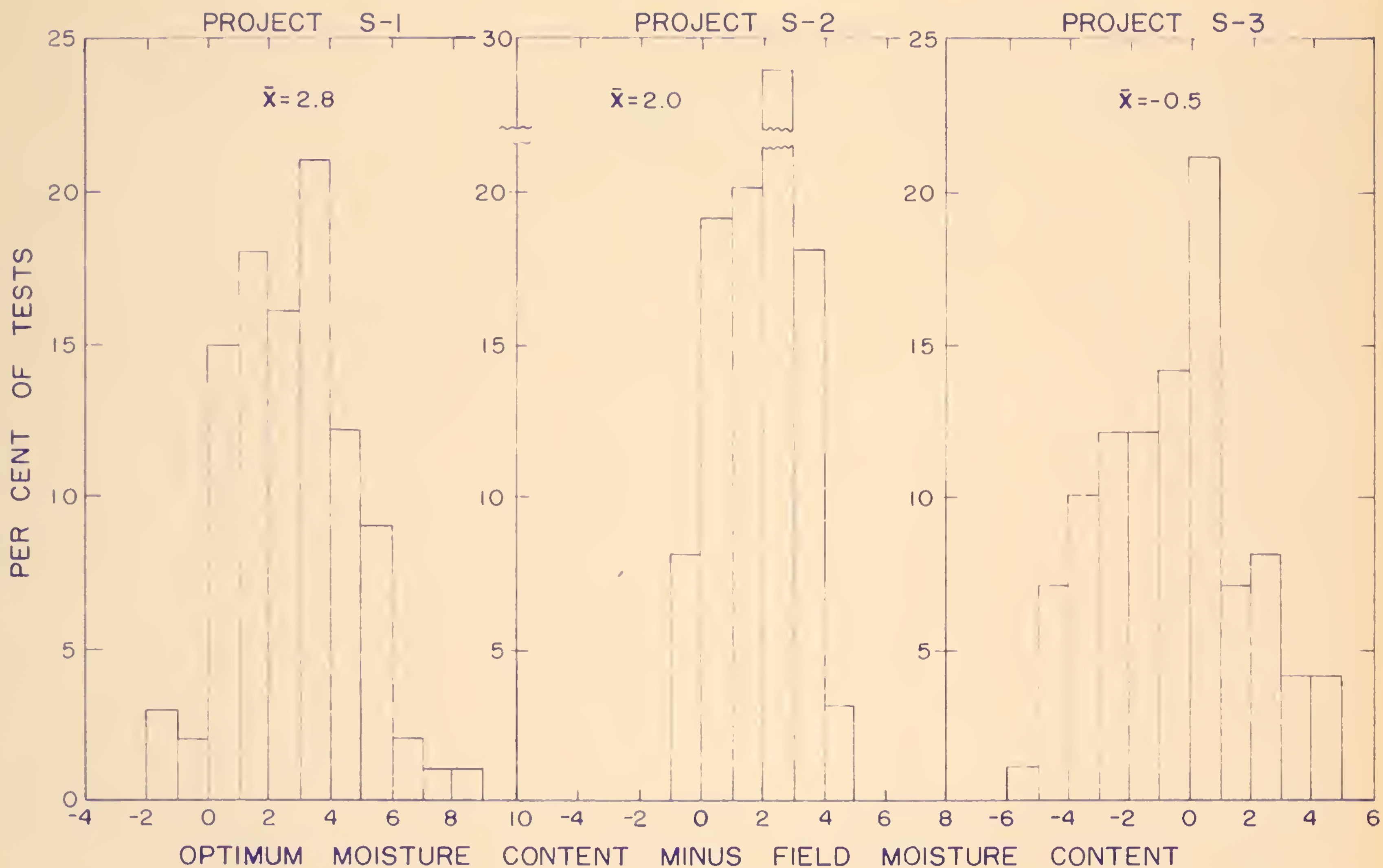


FIGURE 12 FREQUENCY HISTOGRAMS OF OPTIMUM MOISTURE CONTENT MINUS FIELD MOISTURE CONTENT FOR THREE SUBGRADE PROJECTS

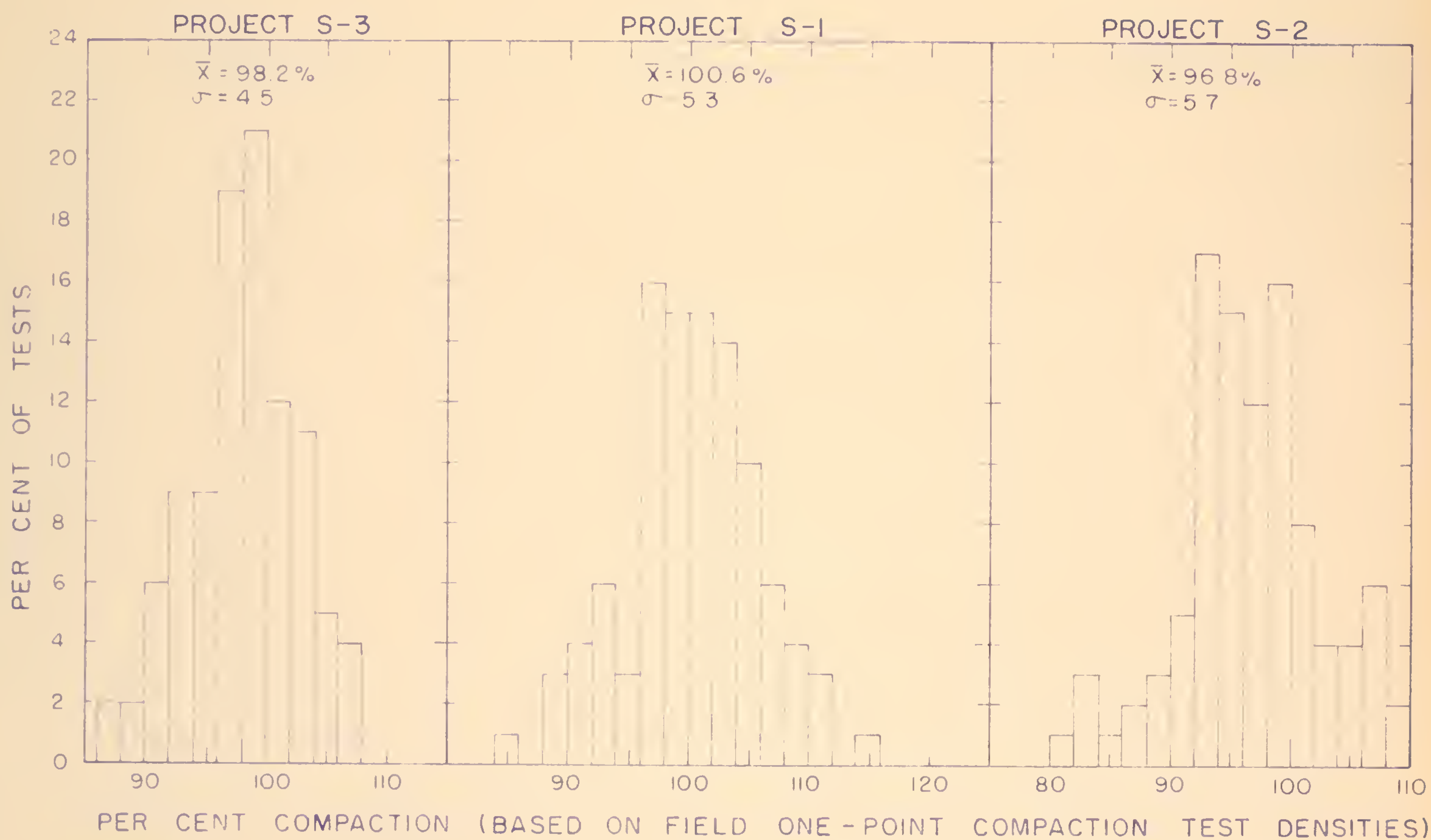


FIGURE 13 FREQUENCY HISTOGRAMS OF PER CENT COMPACTION OF SUBGRADE MATERIALS FOR THREE PROJECTS

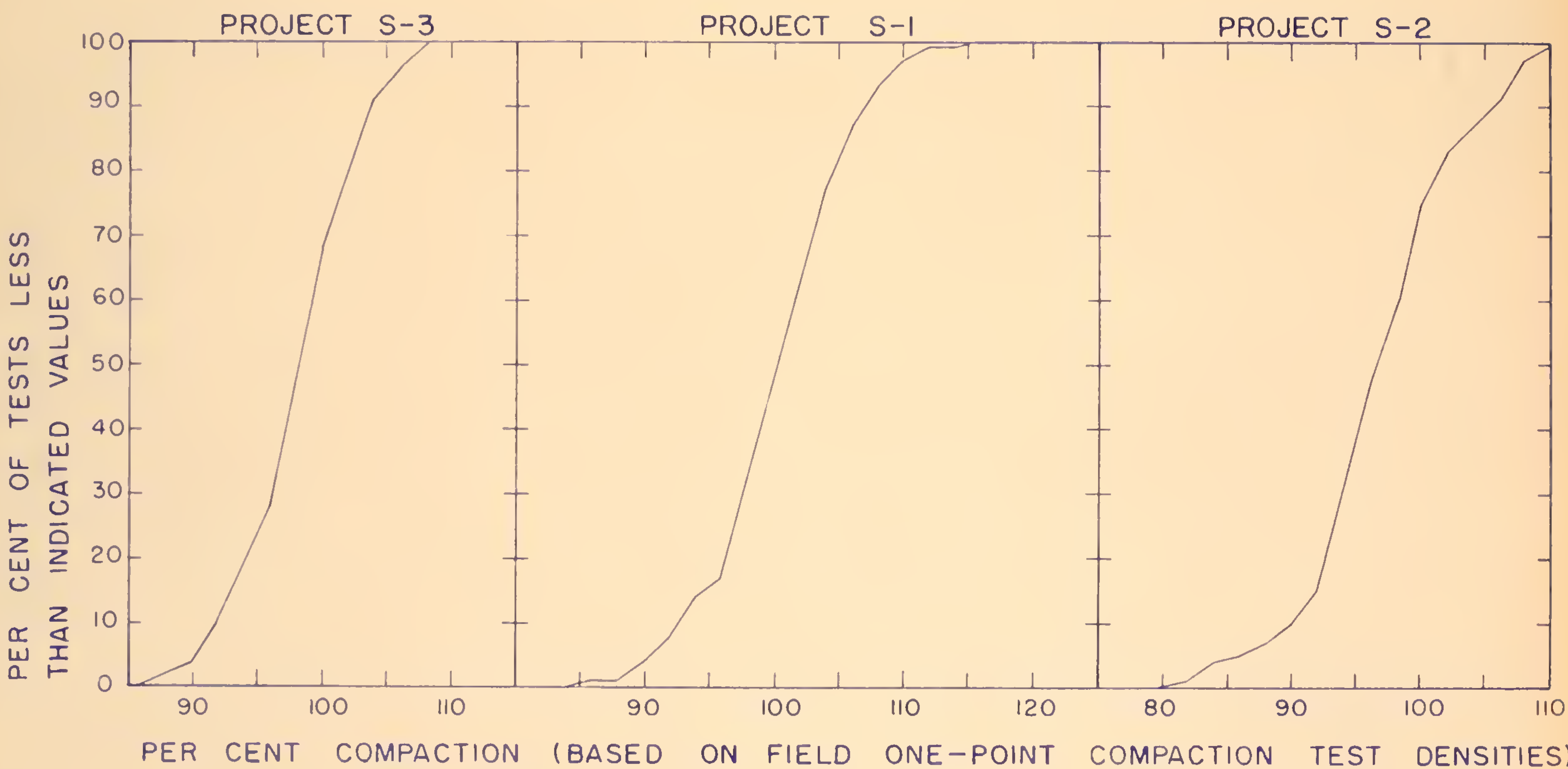


FIGURE 14 CUMULATIVE POLYGONS OF PER CENT COMPACTION OF SUBGRADE MATERIALS FOR THREE PROJECTS

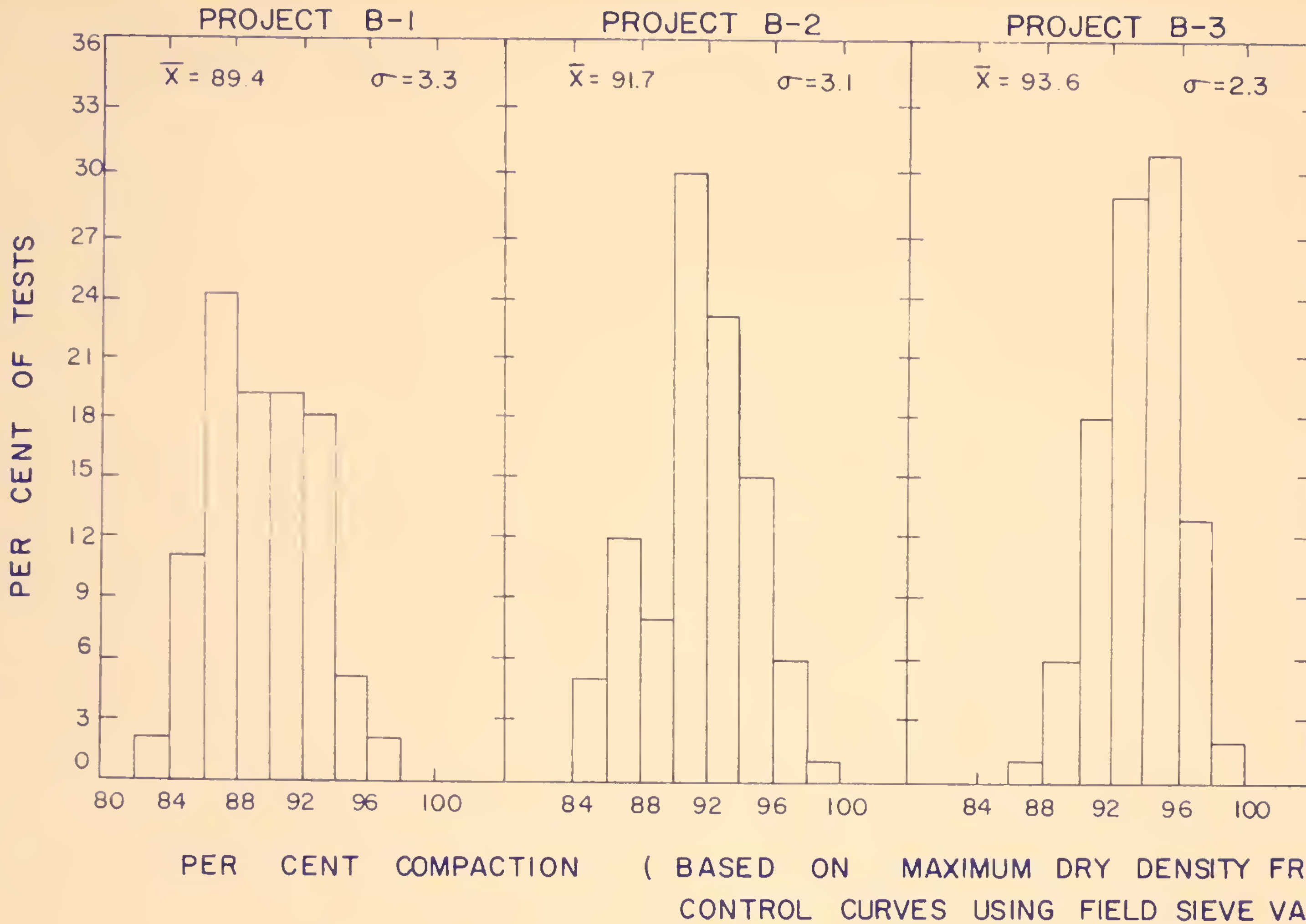


FIGURE 15 FREQUENCY HISTOGRAMS OF PER CENT COMPACTION OF SUBBASE MATERIALS FOR THREE PROJECTS

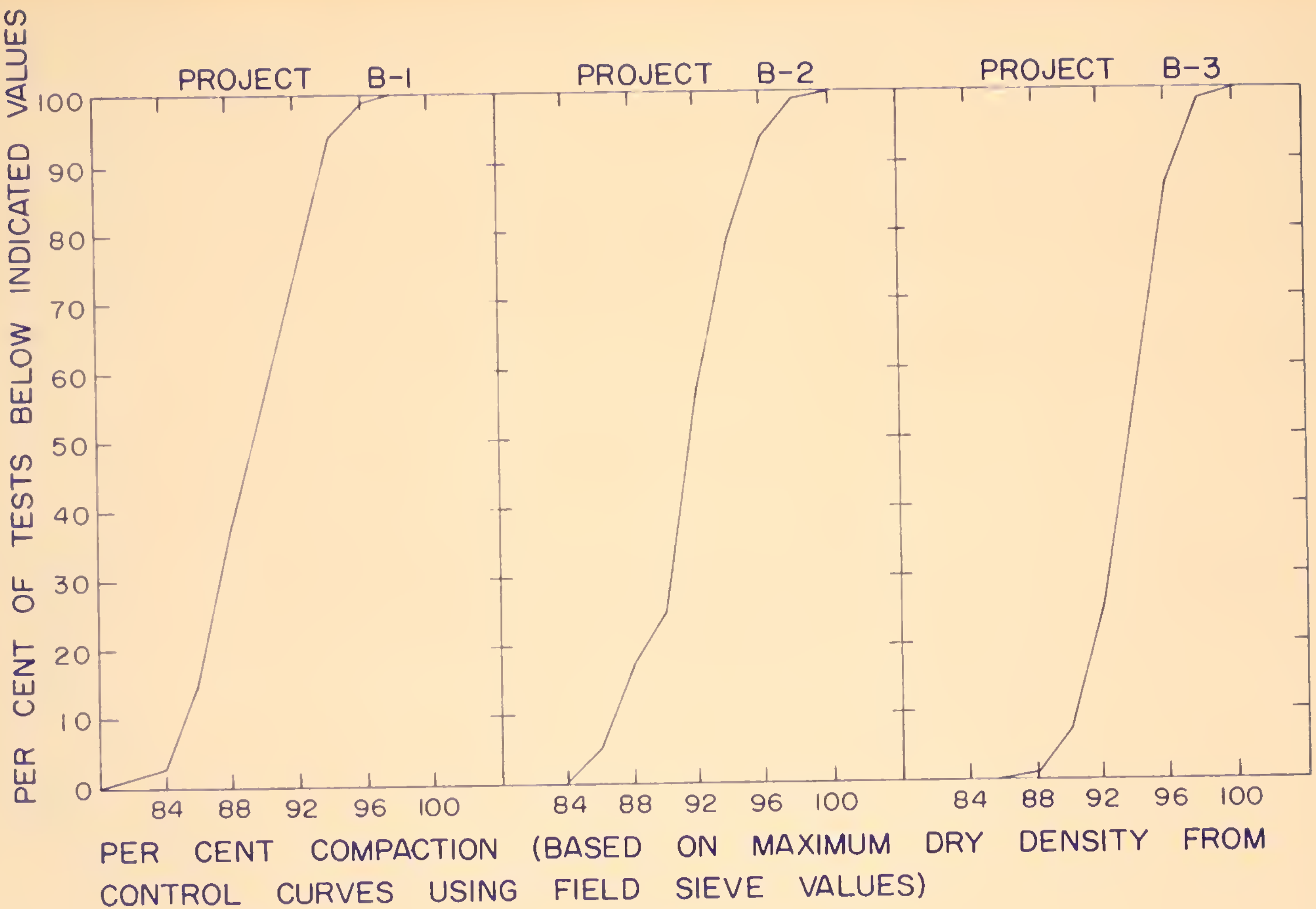


FIGURE 16 CUMULATIVE POLYGONS OF PER CENT COMPACTION OF SUBBASE MATERIALS FOR THREE PROJECTS

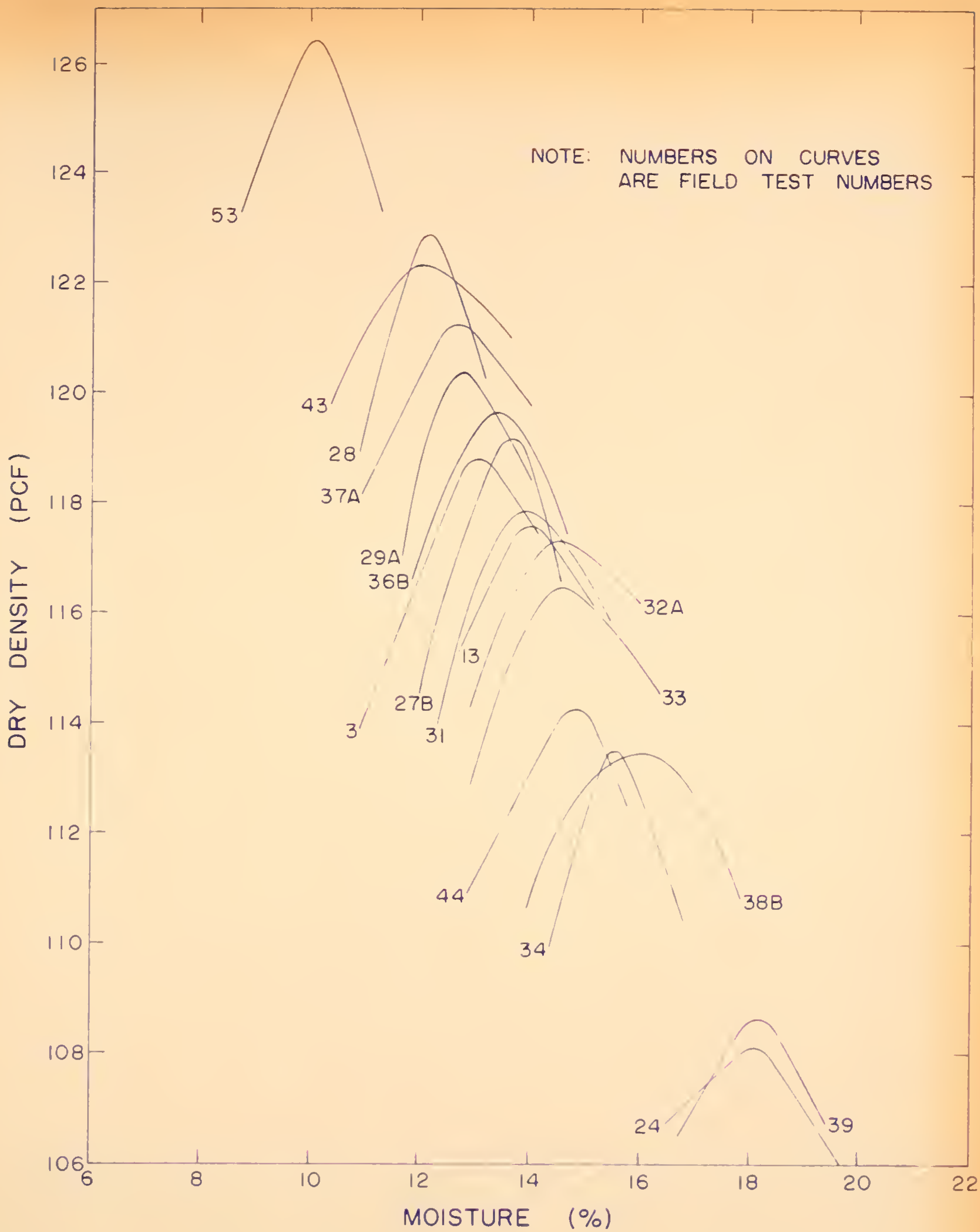


FIGURE 17 DRY DENSITY vs. MOISTURE CONTENT (PROJECT S-1 SUBGRADE SOILS)

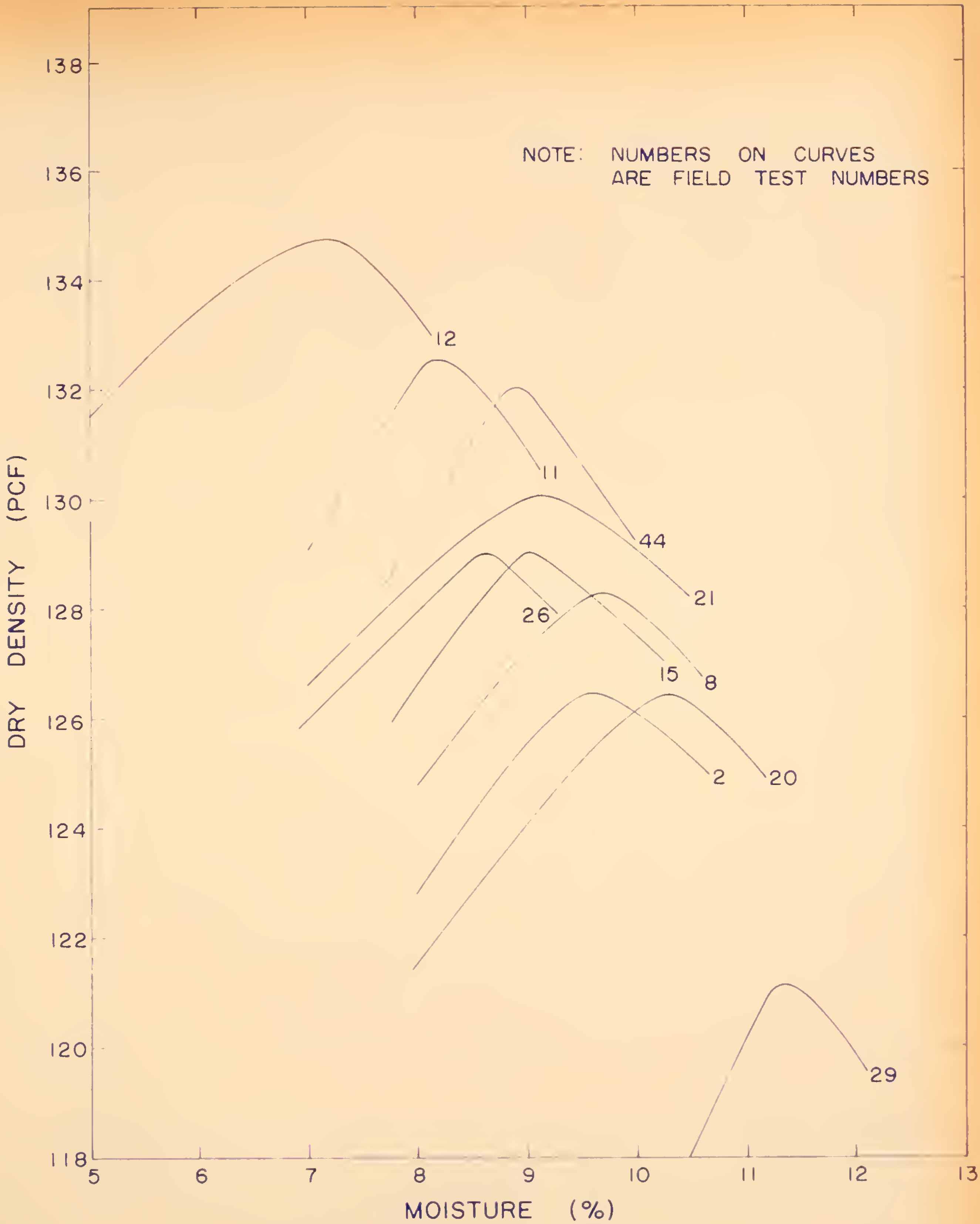


FIGURE 18 DRY DENSITY vs. MOISTURE CONTENT (PROJECT S-2 SUBGRADE SOILS)

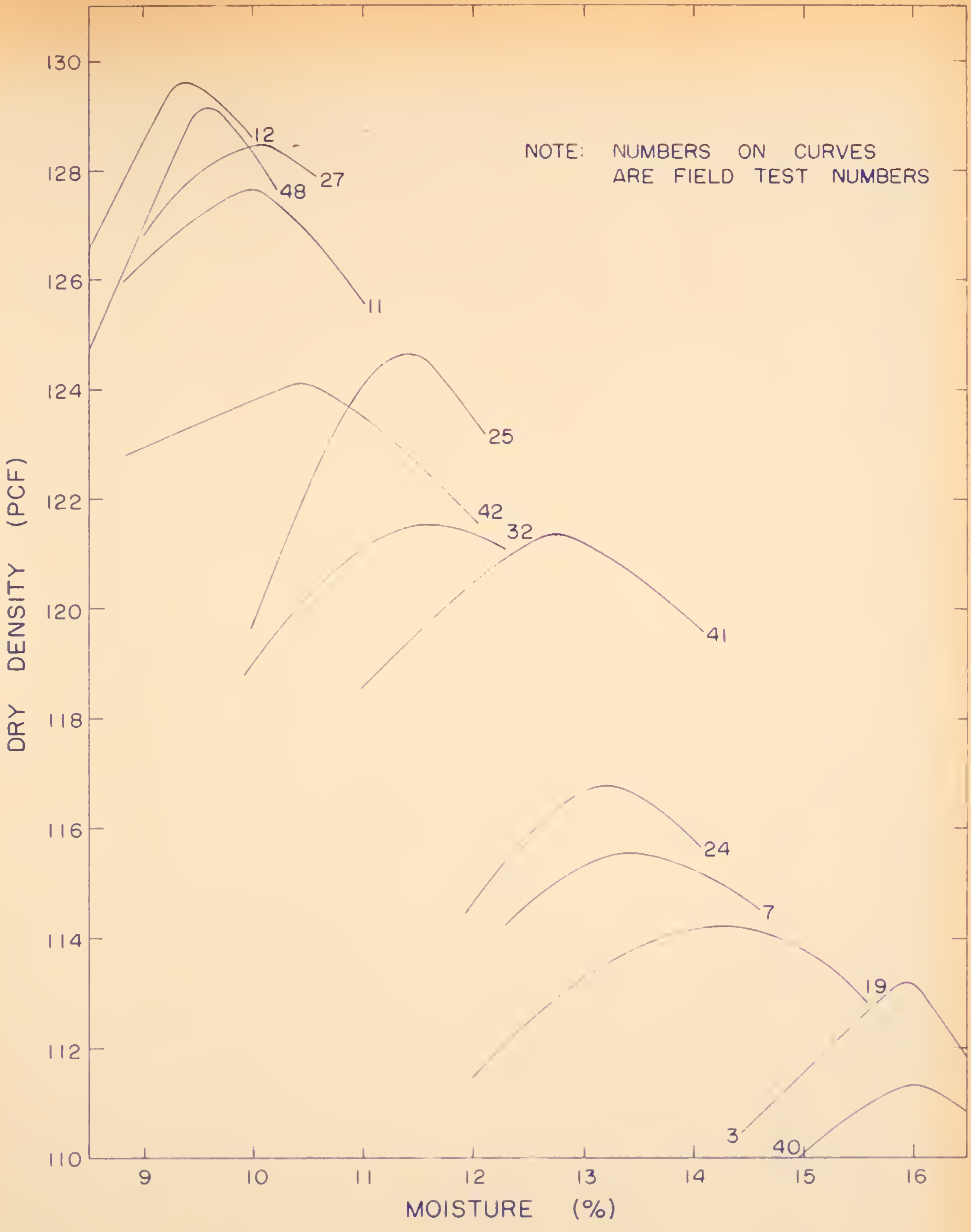


FIGURE 19 DRY DENSITY vs. MOISTURE CONTENT (PROJECT S-3 SUBGRADE SOILS)

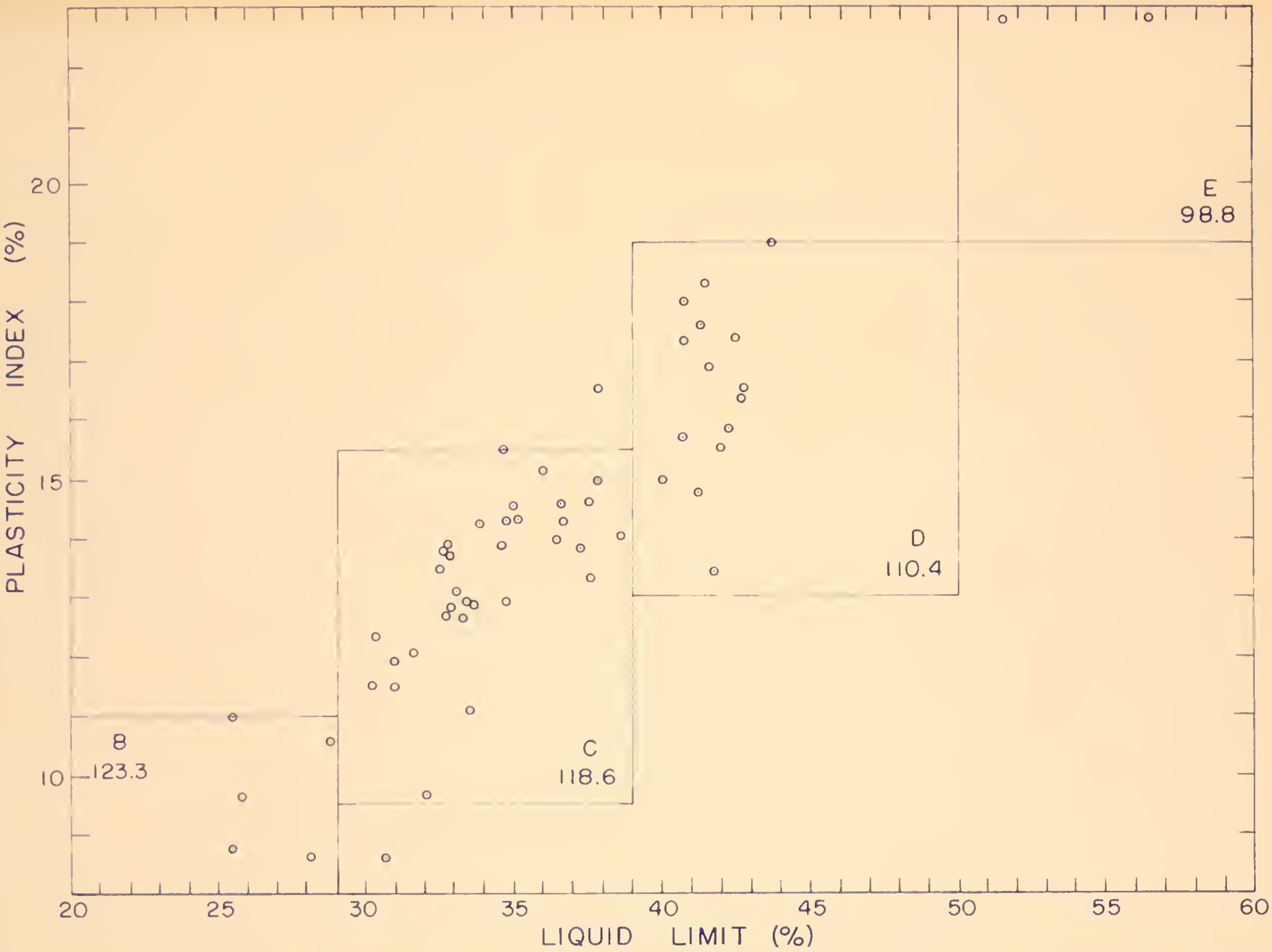


FIGURE 20 LIQUID LIMIT vs. PLASTICITY INDEX FOR SUBGRADE SAMPLES SHOWING ASSUMED SOIL CLASSIFICATION GROUPINGS AND AVERAGE MAXIMUM DRY DENSITY FROM LABORATORY TESTS FOR EACH GROUP (PROJECT S-1)

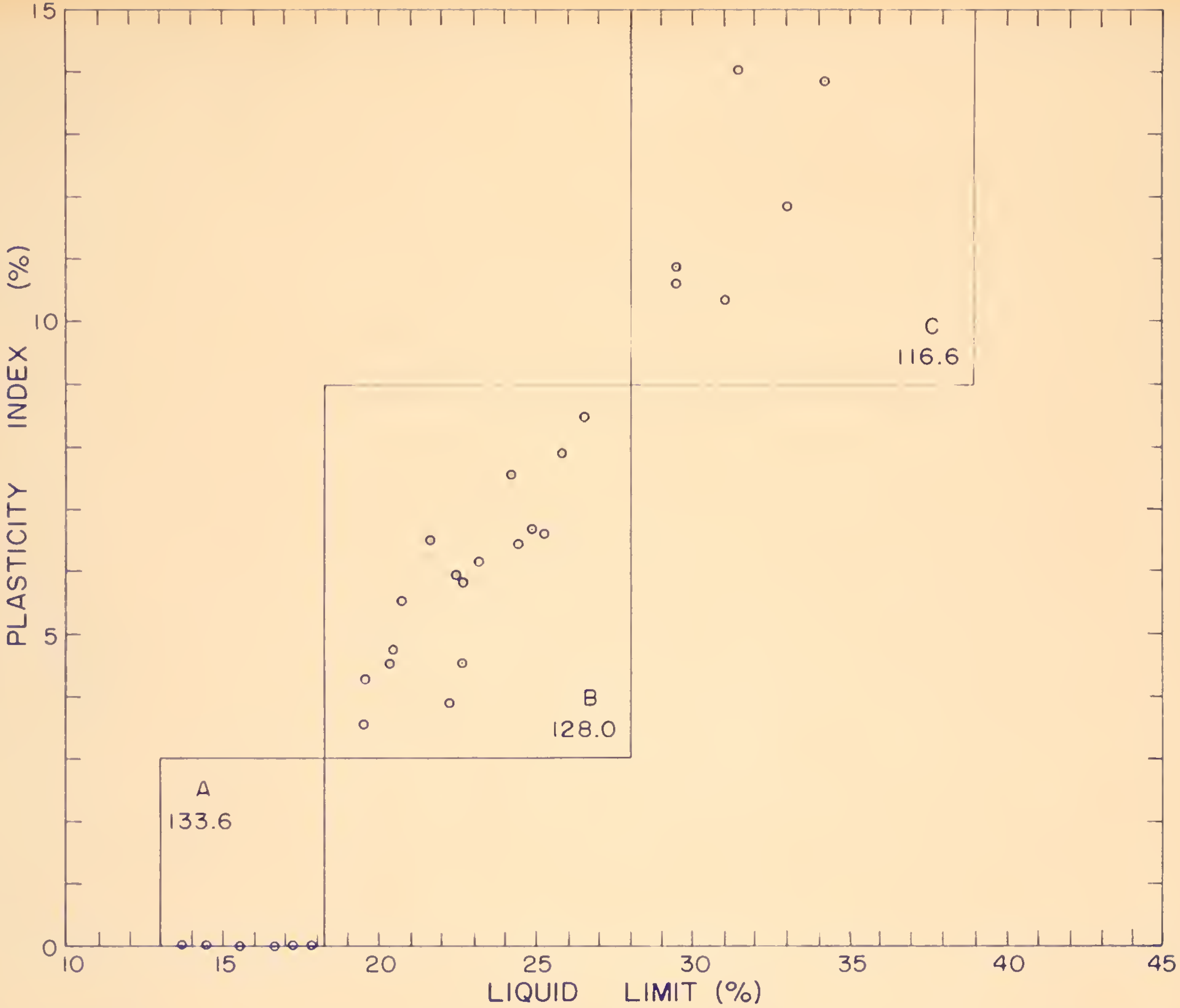


FIGURE 21 LIQUID LIMIT vs. PLASTICITY INDEX FOR SUBGRADE SAMPLES SHOWING ASSUMED SOIL CLASSIFICATION GROUPINGS AND AVERAGE MAXIMUM DRY DENSITY FROM LABORATORY TESTS FOR EACH GROUP (PROJECT S-2)

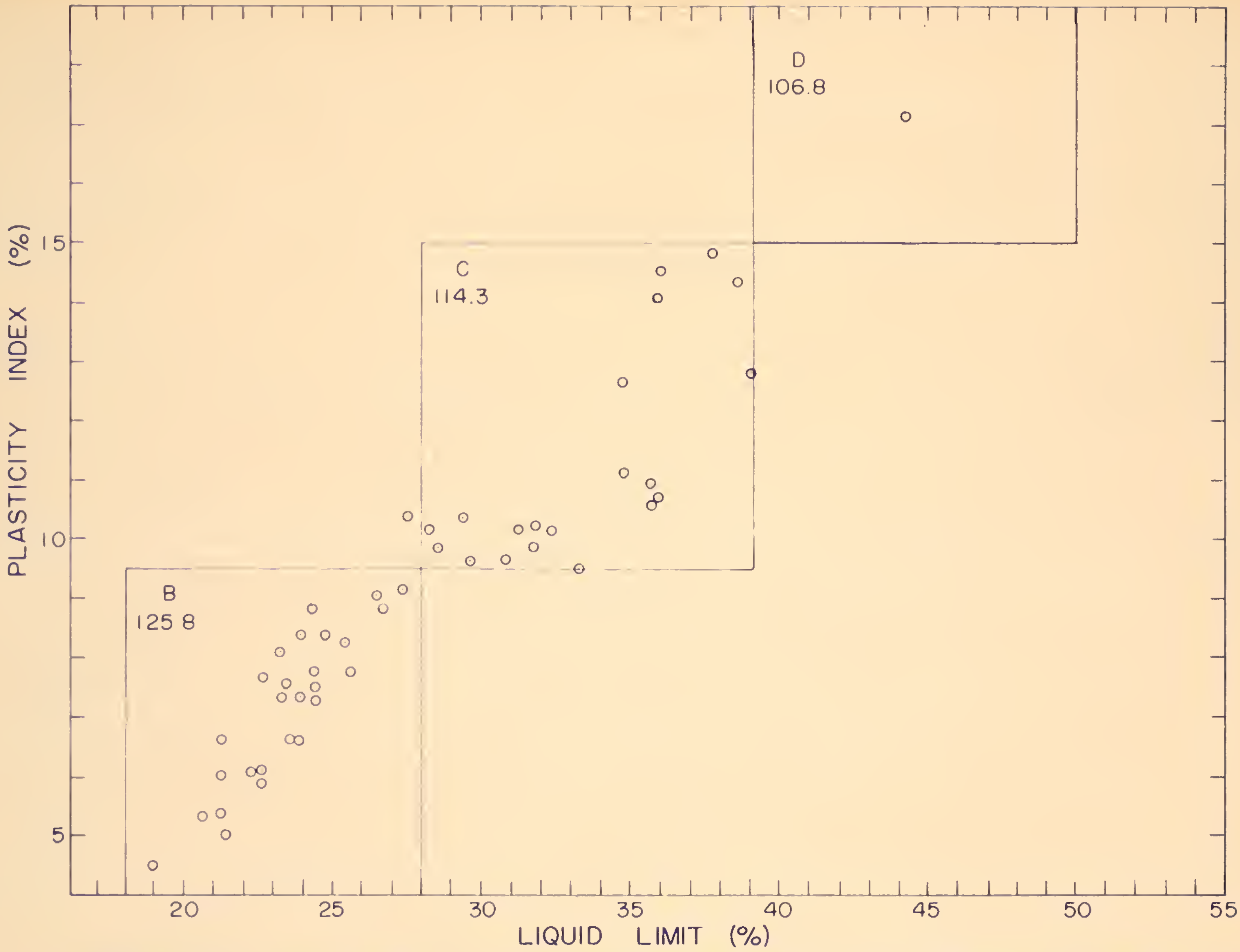


FIGURE 22 LIQUID LIMIT vs. PLASTICITY INDEX FOR SUBGRADE SAMPLES SHOWING ASSUMED SOIL CLASSIFICATION GROUPINGS AND AVERAGE MAXIMUM DRY DENSITY FROM LABORATORY TESTS FOR EACH GROUP (PROJECT S-3)

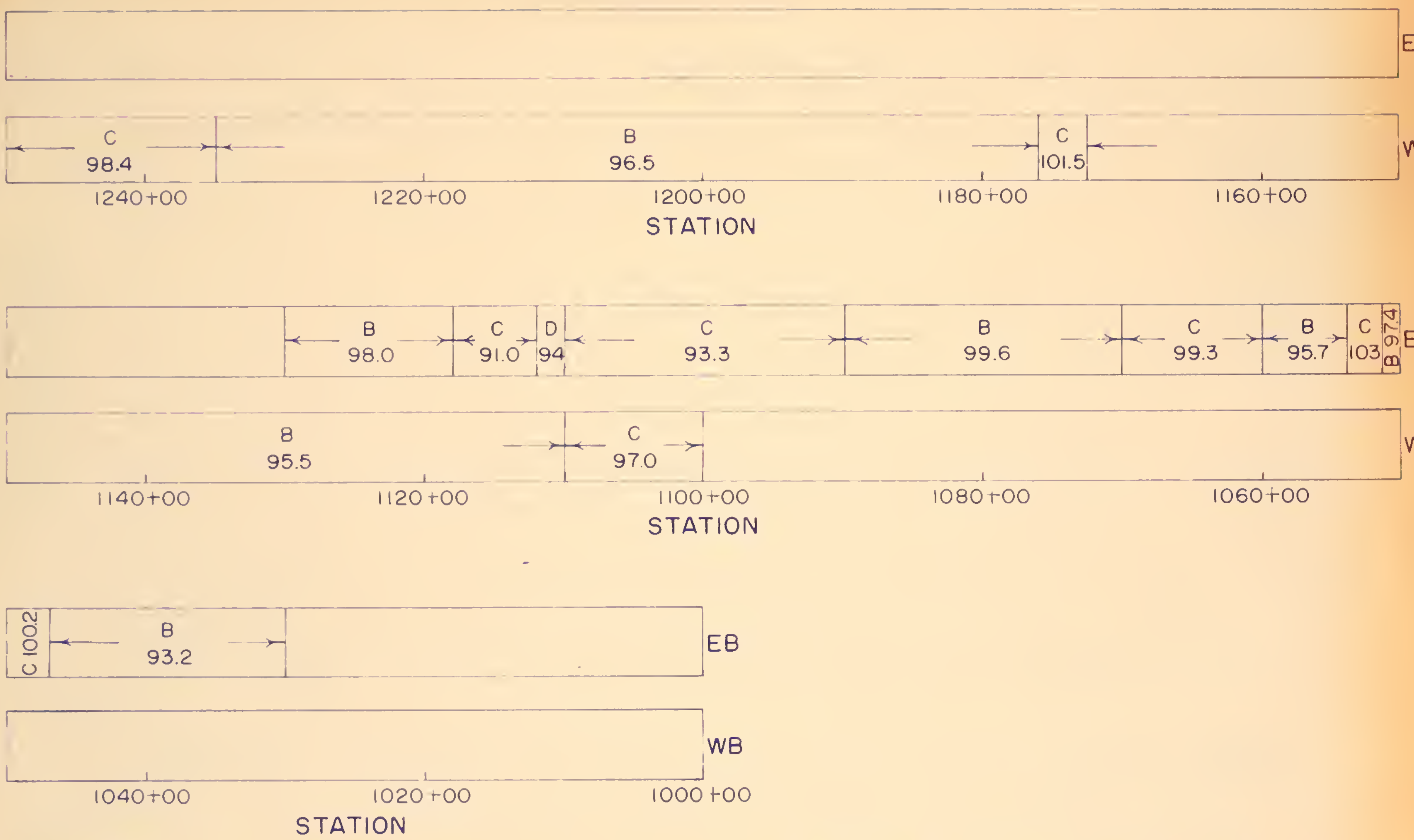


FIGURE 23 LOCATION OF SUBGRADE SOIL TYPES SHOWING AVERAGE PER CENT COMPACTION FOR EACH SECTION BASED ON SOIL CLASS GROUP MAXIMUM DRY DENSITY (PROJECT S-3)

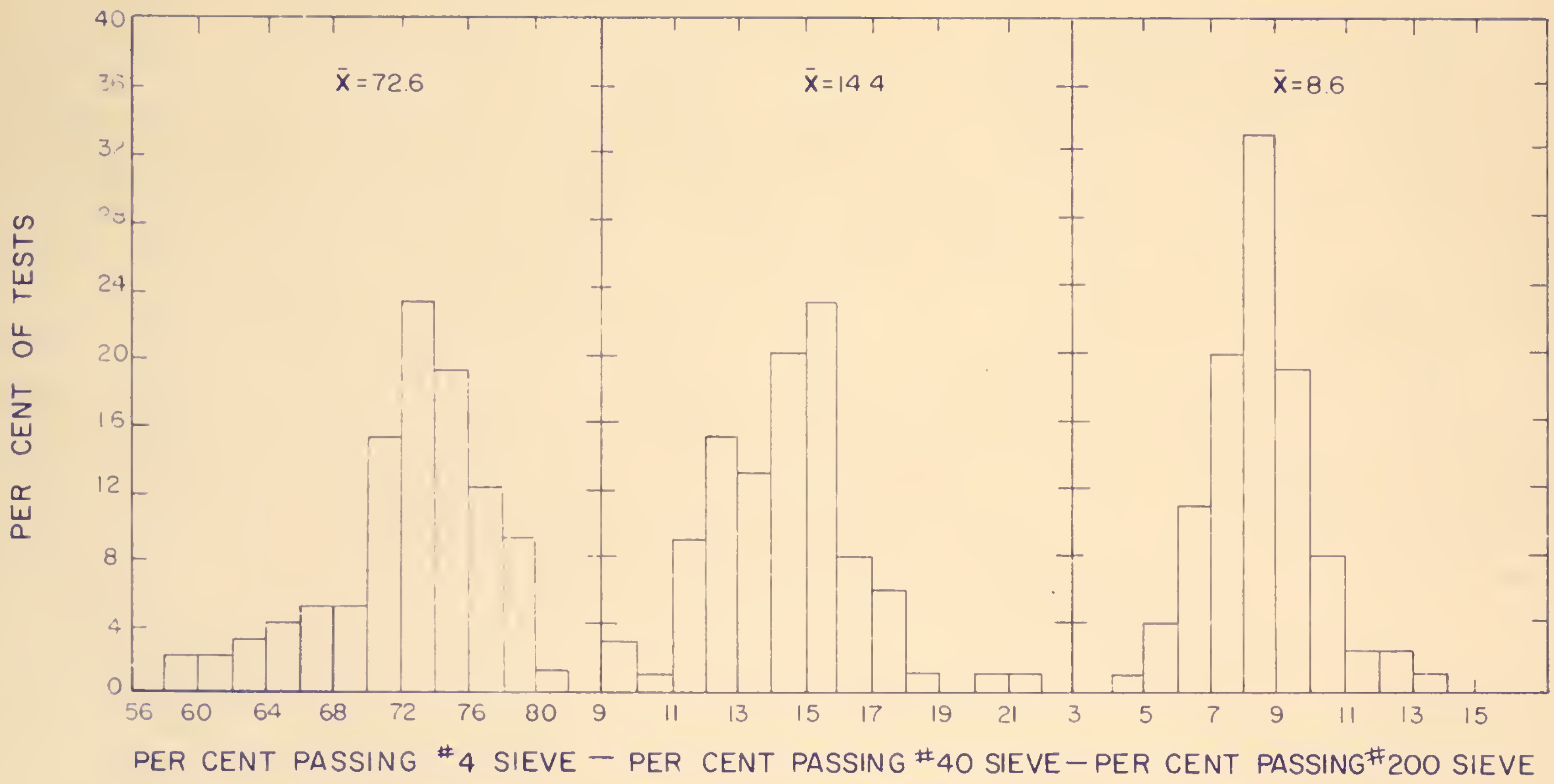
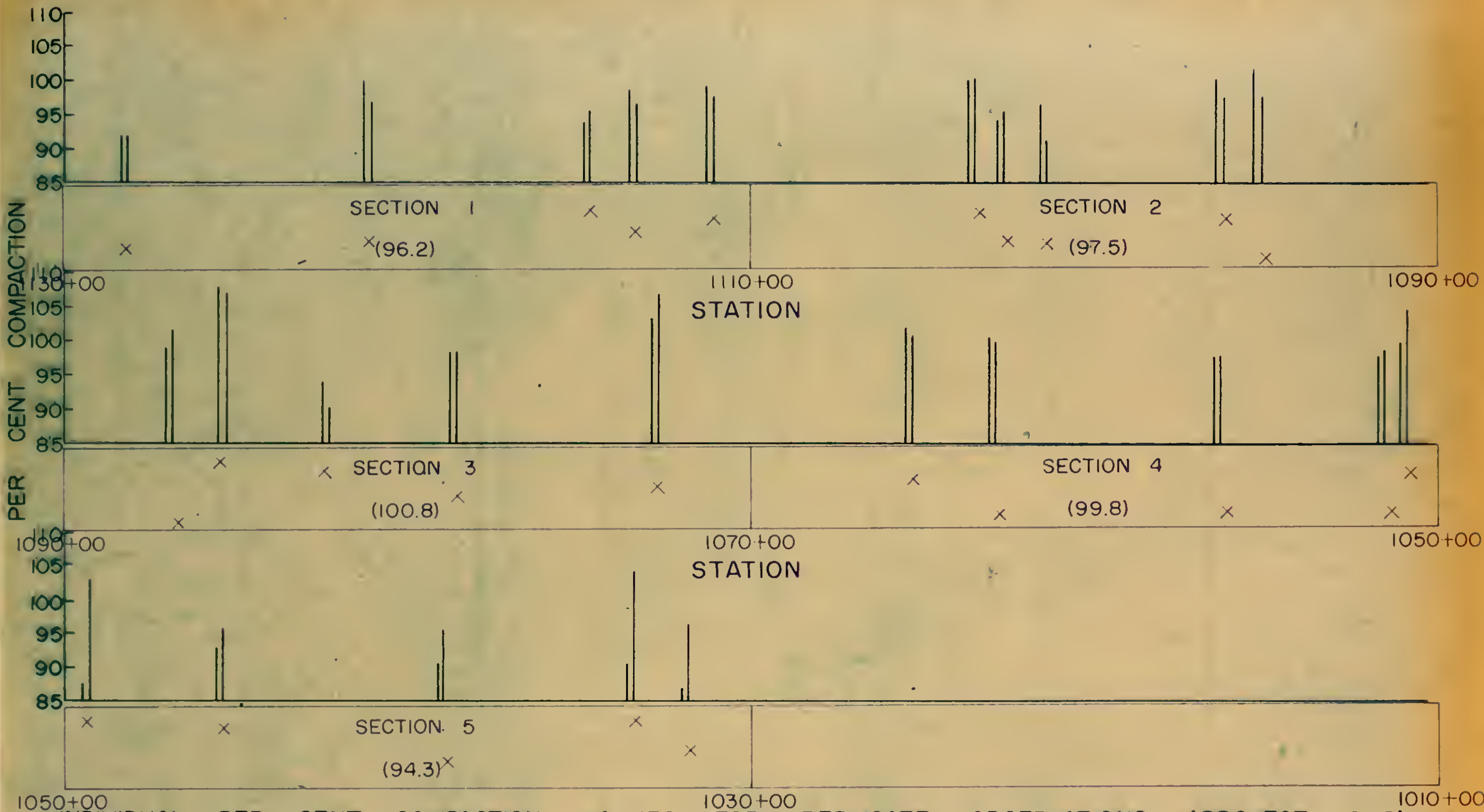
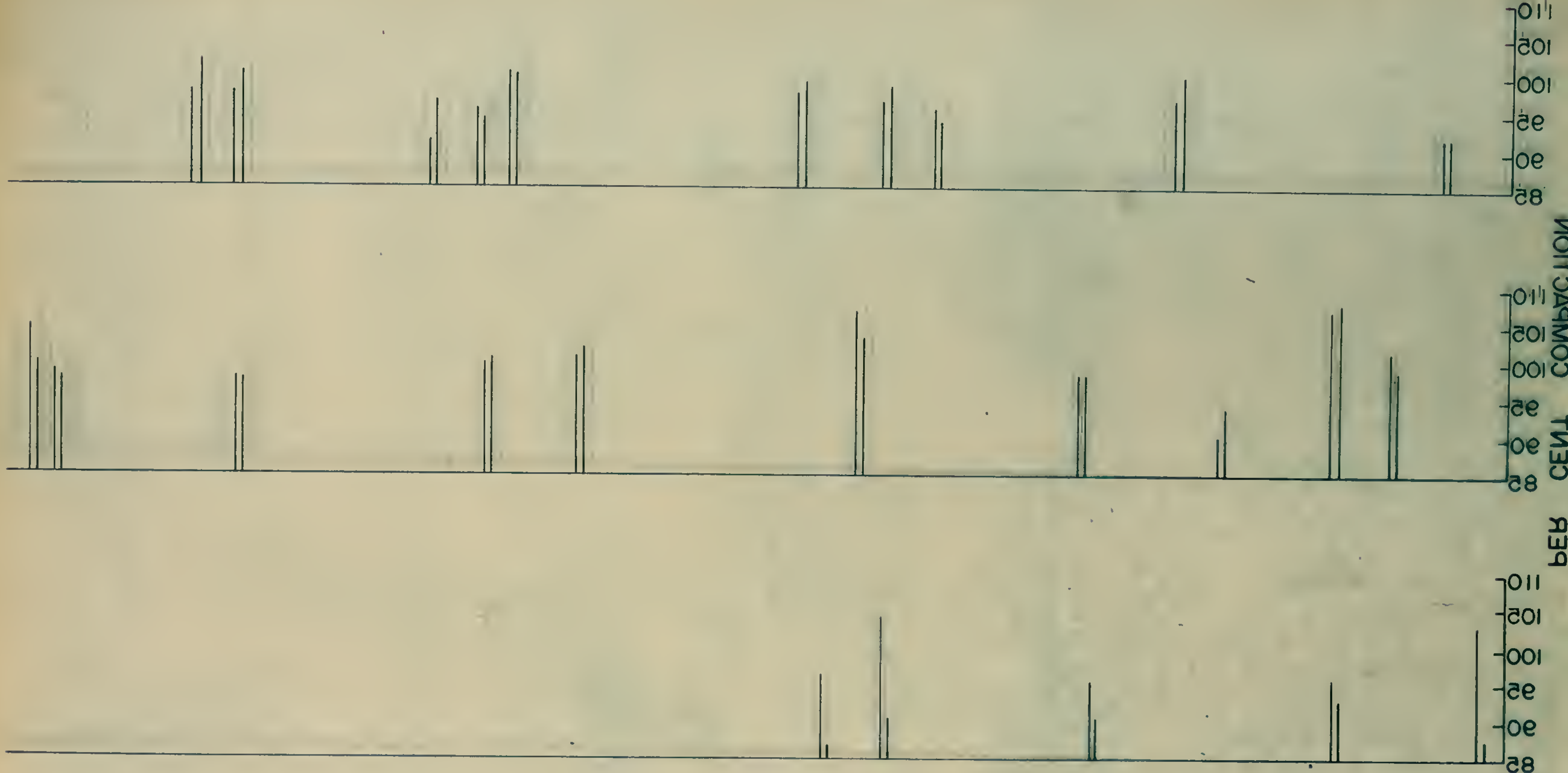


FIGURE 24 FREQUENCY HISTOGRAMS OF GRAIN SIZE DISTRIBUTION FOR THREE SIEVE SIZES FOR SUBBASE MATERIAL FROM PROJECT B-1 (BASED ON LABORATORY VALUES)



INDIVIDUAL PER CENT COMPACTION VALUES FOR REPLICATE OBSERVATIONS (PROJECT S-3)

FIGURE 25 SUBGRADE TEST LOCATIONS SHOWING AVERAGE PER CENT COMPACTION BASED ON ONE-POINT COMPACTION MAXIMUM DRY DENSITIES FOR EACH ORIGINAL 2000 FOOT TEST CONTROL SECTION (EAST BOUND LANE, PROJECT S-3)



INDIVIDUAL PER CENT COMPACTION VALUES FOR REPLICATE OBSERVATIONS (PROJECT S-3)

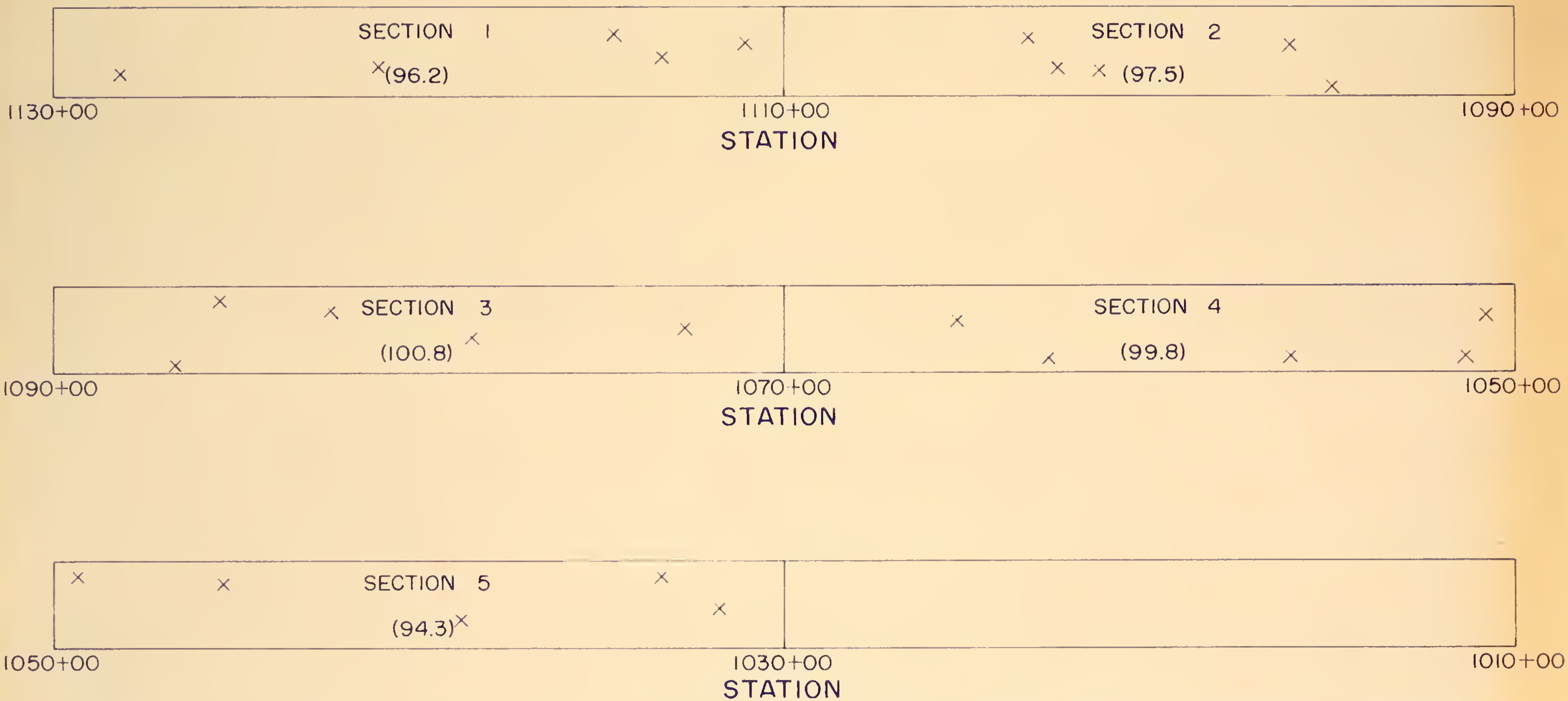
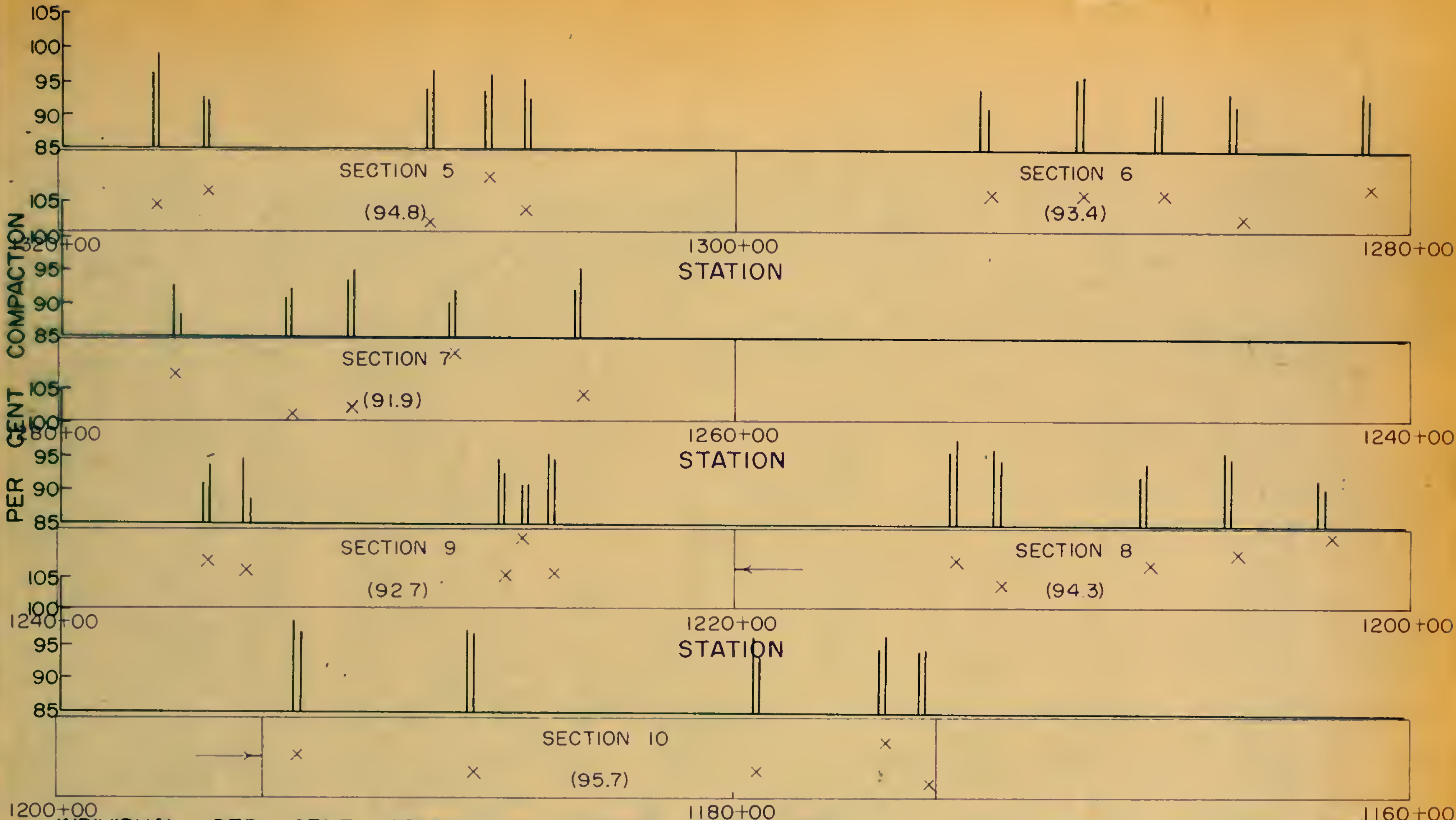


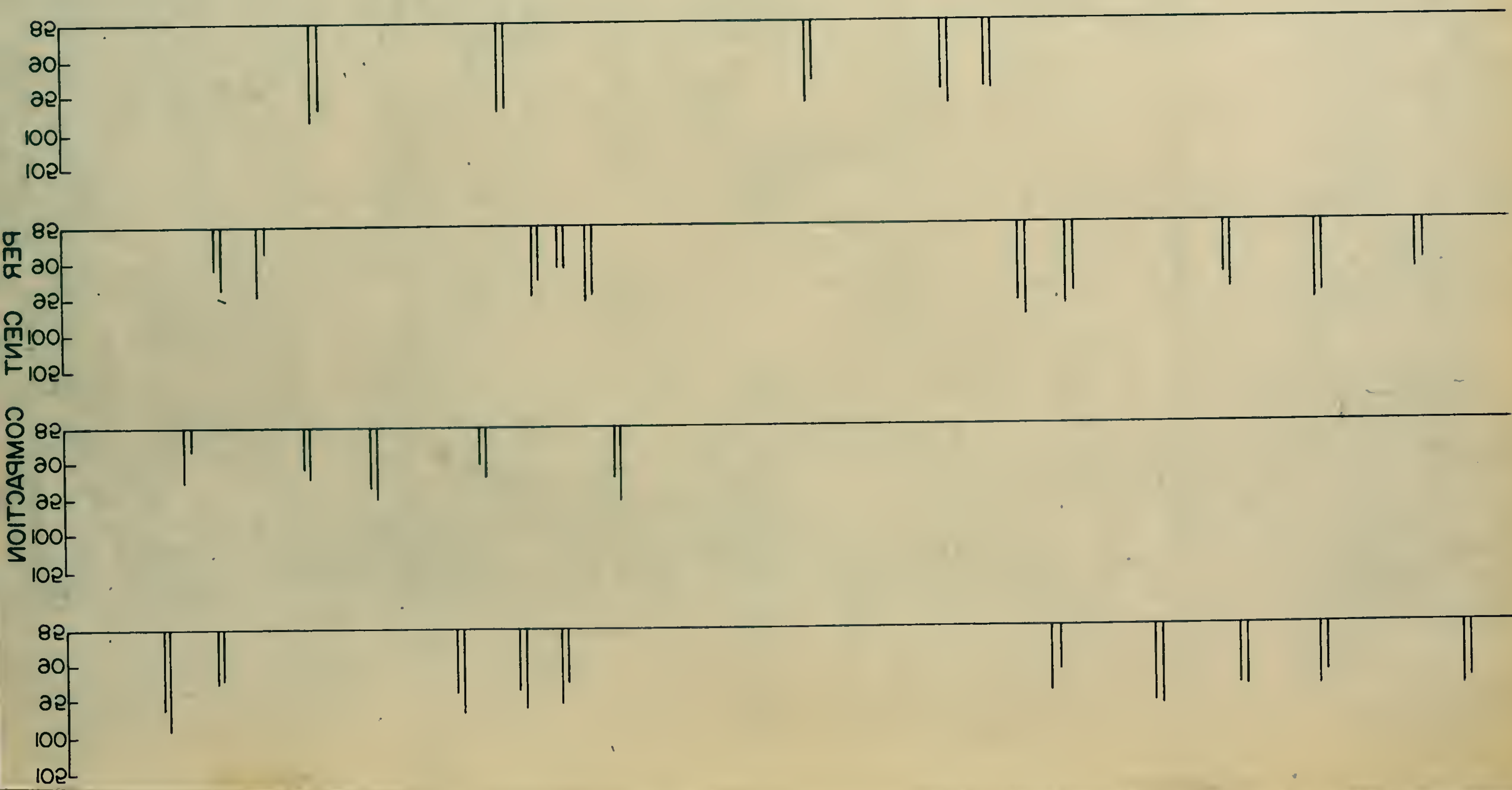
FIGURE 25 SUBGRADE TEST LOCATIONS SHOWING AVERAGE PER CENT COMPACTION BASED ON ONE-POINT COMPACTION MAXIMUM DRY DENSITIES FOR EACH ORIGINAL 2000 FOOT TEST CONTROL SECTION (EAST BOUND LANE, PROJECT S-3)



INDIVIDUAL PER CENT COMPACTION VALUES FOR REPLICATE OBSERVATIONS (PROJECT B-3)

FIGURE 26 SUBBASE TEST LOCATIONS SHOWING AVERAGE PER CENT COMPACTION VALUES BASED ON CONTROL CURVE MAXIMUM DRY DENSITIES FOR ORIGINAL 2000 FOOT TEST CONTROL SECTIONS (WEST BOUND LANE, PROJECT B-3)

INDIVIDUAL PER CENT COMPACTION VALUES FOR REPLICATE OBSERVATIONS (PROJECT B-3)



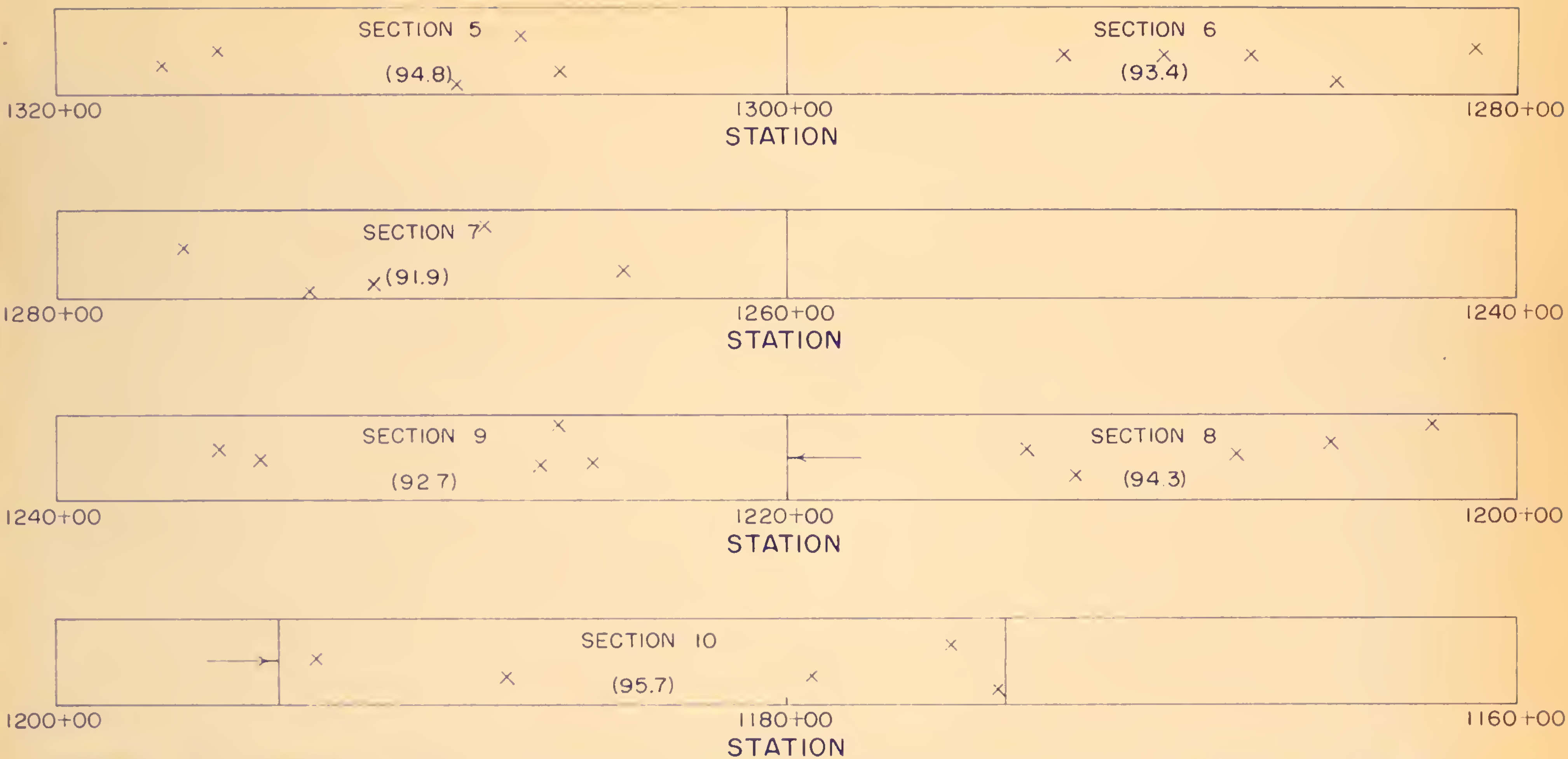


FIGURE 26 SUBBASE TEST LOCATIONS SHOWING AVERAGE PER CENT COMPACTION VALUES BASED ON CONTROL CURVE MAXIMUM DRY DENSITIES FOR ORIGINAL 2000 FOOT TEST CONTROL SECTIONS (WEST BOUND LANE, PROJECT B-3)

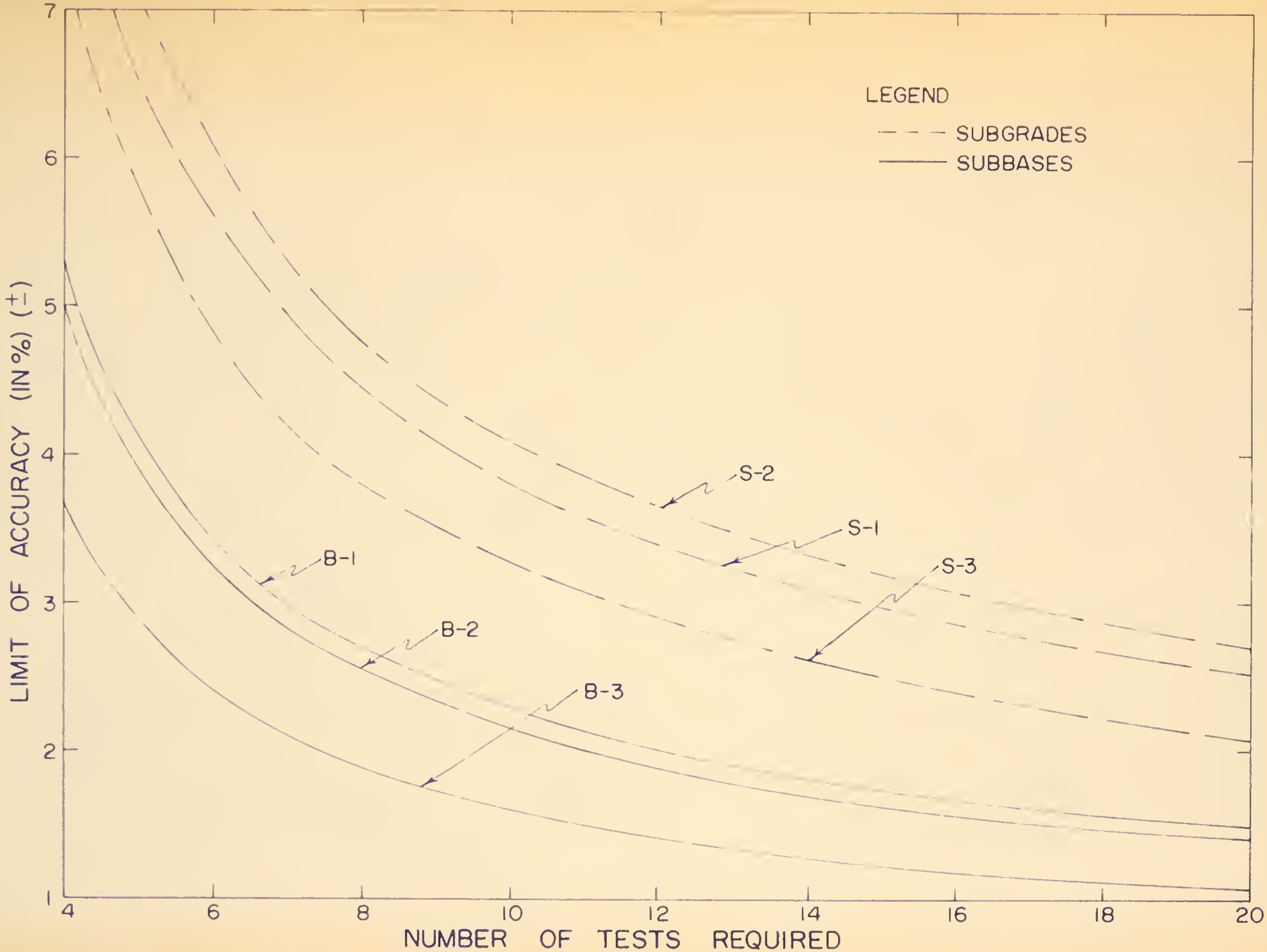


FIGURE 27 LIMIT OF ACCURACY vs. NUMBER OF TESTS REQUIRED FOR PER CENT COMPACTION